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In Situ Remediation of a TCE-Contaminated Aquifer Using a Short Rotation Woody Crop Groudwater Treatment System

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ACRONYMS AND ABBREVIATIONS

ASC/ENV	Aeronautical Systems Center/Engineering Directorate
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAA	Clean Air Act
CGC	Carswell Golf Course
*c*DCE	*cis*-1,2-dichloroethene
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CH_4	methane
CO_2	carbon dioxide
CWA	Clean Water Act
D	hydrogen isotope
DO	dissolved oxygen
DOC	Dissolved Organic Carbon
DoD	Department of Defense
DOE	Department of Energy
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FRTR	Federal Remediation Technologies Roundtable
FS	Forest Service
GC	gas chromatograph
g	gram
gal. day^{-1}	gallons per day
gal. $tree^{-1}$ day^{-1}	gallons per tree per day
H_2	hydrogen gas
ha	hectare
i	Hydraulic Gradient
ICP	inductively coupled plasma
IRP	Installation Restoration Program
ITER	Innovative Technology Evaluation Report
K	hydraulic conductivity
K_{ow}	Octanol-water partition coefficient
kg	kilogram(s)
kg ha^{-1} day^{-1}	kilograms per hectare per day
kg hr^{-1} $tree^{-1}$	kilograms per hour per tree

ACRONYMS AND ABBREVIATIONS (continued)

kg cm^{-2} hr^{-1}	kilograms per square centimeter per hour
L day^{-1}	liters per day
m_f	Mass flux
m	meter
m/d	meters per day
m^2	square meters
m m^{-2}	meter per square meter
m^3/day	cubic meters per day
MCL	maximum contaminant levels
MCLG	maximum contaminant level goals
mg/L	milligrams per liter
mm	millimeter
MPN	most probable number
NAC	Natural attenuation capacity
NAS-JRB	Naval Air Station - Joint Reserve Base
NPDES	National Pollutant Discharge Elimination System
NPL	National Priorities List
ND	Not detected
^{18}O	Oxygen isotope
O&M	operation and maintenance
PCE	perchloroethylene or tetrachloroethylene
PCB	polychlorinated biphenyls
PPE	personal protective equipment
Q	volumetric flux of groundwater
RCRA	Resource Conservation and Recovery Act
SAIC	Science Applications International Corporation
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
STL	Severn Trent Laboratories
SITE	Superfund Innovative Technology Evaluation
SRWC	short rotation woody crop
SRWCGT	short rotation woody crop groundwater treatment
TCE	trichloroethene
*t*DCE	trans-1,2-dichloroethene
TOC	total organic carbon
TSD	treatment, storage and disposal

μg/L	micrograms per liter
μg/kg	micrograms per kilogram
USACE	United States Army Corps of Engineers
USAF	United States Air Force
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VC	vinyl chloride
VOCs	volatile organic compounds

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Urban forester Larry Schaapveld of the Texas State Forest Service made technical contributions and was instrumental in making this project a success. Scientists at Science Applications International Corporation (SAIC), the University of Georgia, the U.S. Forest Service, Environmental Protection Agency (EPA), and U.S. Geological Survey (USGS) conducted work related to secondary project objectives in cooperation with ASC/ENV and the EPA SITE program.

This report is a compilation of the information acquired during the 3-year demonstration (August 1996–September 1998) and additional information acquired from follow-on studies conducted through January 2003.

Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

A field-scale demonstration project was conducted to evaluate the capability of Eastern cottonwood trees (*Populus deltoides*) to intercept and treat groundwater contaminated with trichloroethylene (TCE) and cis-1,2-dichloroethene (*c*DCE) at the Carswell Golf Course (CGC), within the Naval Air Station Joint Reserve Base (NAS-JRB) Fort Worth, Texas (formerly Carswell Air Force Base). Eastern cottonwood trees are classified as a short rotation woody crop (SRWC) because they are fast-growing, easy to regenerate, and a commercially viable source of pulp for paper products.

Specifically, the study was undertaken to determine the potential for a short rotation woody crop groundwater treatment (SRWCGT) system to control hydraulically the migration of a contaminated groundwater plume and to biologically enhance the subsurface environment to optimize in situ reductive dechlorination of the detected chlorinated ethenes (TCE and *c*DCE). Contrary to many conventional treatment processes, a SRWCGT system does not require the addition of chemical or biological enhancements. The SRWCGT system at the CGC consists of two 15 x 75 meter (m) plantations, one planted with 1-year old stem cuttings (whips) and the other planted with 1-year old seedlings (caliper trees).

The original funding for the project came from the DoD's Environmental Security Technology Certification Program (ESTCP) (AFCEE/ERD, 1996). The bulk of the funding for sampling and analysis conducted during the demonstration was provided by the Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program. Follow-on research conducted after the demonstration (between 1998 and 2005) and outside the original ESTCP scope of work was funded by the Air Force.

1.2 OBJECTIVES OF THE DEMONSTRATION

The SRWCGT system at the CGC was initially evaluated under the EPA SITE Program for the first three growing seasons (August 1996 through September 1998). After September 1998, groundwater at the CGC was monitored further to evaluate phytoremediation-induced geochemical changes in the TCE plume, with an emphasis on the relation of biodegradation rates to tree plantation age and associated increases in vegetative biomass (Eberts et al, 2005). During the SITE Program's involvement, the SRWCGT system was evaluated for its ability to reduce the mass of TCE that is transported across the downgradient end of the site (i.e., mass flux). Specific objectives were developed for the August 1996–September 1998 time frame. The primary objective focused on the following two project goals:

(1) There was to be a 30% reduction in the mass of TCE in the aquifer that is transported across the downgradient end of the site during the second growing season, as compared to baseline TCE mass flux calculations.

(2) There was to be a 50% reduction in the mass of TCE in the aquifer that is transported across the downgradient end of the site during the third growing season, as compared to baseline TCE mass flux calculations.

Original objectives were arbitrary (i.e., having been made with little or no knowledge of the capability of the trees to alter either the hydrology or geochemistry of a shallow aquifer (Harvey, 2005).

In addition to the primary performance objective, secondary objectives were included in the project to elucidate the biological, hydrological, and biochemical processes contributing to the effectiveness of phytoremediation of TCE-contaminated groundwater. Much of the data associated with secondary objectives were collected to prepare models for predicting future performance. Secondary objectives included:

- Documenting tree growth rates and root biomass
- Analyzing tree transpiration rates to determine current and future water use
- Analyzing hydrologic effects of tree transpiration on the contaminated aquifer
- Analyzing contaminant uptake into tree organs
- Evaluating the subsurface oxidation reduction processes in groundwater
- Evaluating microbial contributions to reductive dechlorination.

1.3 REGULATORY DRIVERS

The target contaminants for the SRWCGT treatment system at the CGC site are chlorinated organic compounds. Although TCE was the focus of the demonstration, other chlorinated organic compounds detected in the groundwater or plant tissue included, but were not limited to, *c*DCE, trans-1,2-dichloroethylene (*t*DCE), tetrachloroethene (PCE), methylene chloride, toluene, and vinyl chloride (VC). The regulatory drivers for these environmental contaminants are maximum contaminant levels (MCL). Table ES-1 lists federal MCLs and maximum contaminant level goals (MCLG) in groundwater for these compounds. MCLs and MCLGs are governed under the Safe Drinking Water Act (SWDA).

Table ES-1. Regulatory Drivers for the Contaminants at the CGC NAS-JRB.

Analyte	MCL (µg/L)[1]	MCLG (µg/L)[2]	Potential Health Effects from Ingested Water
TCE	5	0	Liver problems; increased risk of cancer
*c*DCE	70	70	Liver problems
*t*DCE	100	100	Liver problems
TCE	5	0	Liver problems; increased risk of cancer
Methylene Chloride	5	0	Liver problems; increased risk of cancer
Toluene	1000	1000	Nervous system, kidney, or liver problems
VC 3	2	0	Increased risk of cancer

[1] An MCL is the highest level of a contaminant allowed in drinking water.
[2] An MCLG is the level of a contaminant in drinking water below which there is no known or expected risk to health.
[3] VC was detected in 6 wells by July 2001 at concentrations ranging from 14-28 µg/L (Eberts et al, 2005).
Source: http://www.epa.gov/safewater/mcl (accessed October 2004)

1.4 DEMONSTRATION RESULTS

The SRWCGT system did not achieve the mass flux reductions of 30% and 50% for the second and third growing seasons, respectively. For the second growing season, the TCE mass flux was actually up 8% during season's peak, as compared to baseline conditions. The planted trees reduced the outward flux of groundwater by 5% during the peak of the second season, but TCE concentrations in a row of wells immediately downgradient of the trees were higher, resulting in the increase in TCE mass flux. For the third growing season, the TCE mass flux was down 11% at peak season and down 8% near season's end, as compared to baseline conditions. Concentrations of TCE during the third season in the row of downgradient wells were similar to concentrations at baseline, and the reduction in TCE mass flux is primarily attributed to a reduction in the volumetric flux of groundwater out of the site (EPA, 2003).

The primary objective was not met because the trees did not reach their full transpiration potential during the time period of the demonstration study, but greater hydraulic control at the site is anticipated in the future.

According to Harvey (2005), "It is unrealistic to see mass flow reductions with only two or three growing seasons" due to "insufficient above and below ground biomass." As a result, models were used to predict the full remediation potential of the tree plantations. These models extrapolated current transpirational hydrologic conditions to future years, i.e., to predict contaminant mass flux, and to predict future biodegradation rates. The models included:

- PROSPER, a physiologically-based model (having the groundwater flow code MODFLOW) was used to predict out-year transpiration rates and the magnitude and extent of future drawdown cones (USEPA, 2003). The model predicted that:
  - The whip and caliper tree plantations will eventually transpire a similar amount of water per growing season, depending on climatic conditions, soil moisture, and root growth.
  - Of this predicted evapotranspiration, 48%-58% is expected to be derived from the contaminated aquifer regardless of planting strategy (USEPA, 2003).
  - Predicted drawdown during peak growing season after the trees have achieved a closed canopy (year 12 and beyond) ranges from 12 to 25 cm at the center of the drawdown cone. The diameter of the predicted drawdown cone ranges from approximately 140 m to more than 210 m (USEPA, 2003).

- BIOCHLOR, an analytical solute transport model was used to estimate first order biodegradation rates along the centerline of the TCE plume for TCE, *c*DCE, and VC for conditions at baseline (1996) and during the sixth growing season (2001). Among other estimations, the model predicted that:
  - There were notable increases in estimated first order biodegradation rate constants for sequential reductive dechlorination of TCE, *c*DCE, and VC (from 1996 baseline conditions to July 2001).
  - The transformation of chlorinated compounds associated with in situ biodegradation may have resulted in a 44% decrease in mass flux of TCE along a simulated flow path during July 2001.

- Based on the predicted 44% decrease in TCE mass flux, and on sap flow and groundwater flow models estimating a transpiration potential of 20% for the plantations, in situ biodegradation is becoming the dominant process contributing to the reduction of TCE mass flux at the site (Eberts et al, 1999).

Follow-on studies (i.e., post-demonstration) involved evaluating long-term geochemical changes in groundwater, water level variations and their effects on tree growth and mortality, uptake of groundwater versus surface water by the Eastern cottonwood trees, and tree coring as a technique. The studies are documented in four published references, summarized as follows:

- Braun et al (2004) investigated biogeochemical parameters and water-level variations at the demonstration site and how the water-level variations affected tree growth and mortality. As of January 2003, mortality rates in both plantations have been significant. In the whip plantation, mortality increased substantially where groundwater depth exceeded 10 ft and approached 90% for groundwater depths between 12 and 13 ft. (i.e., 189, or 43%, of trees in the whip plantation had died). Almost one-half (49%) of the trees in the caliper plantation were either stunted by beaver activity (40%) or altered by human activities (9%).

- Eberts et al (2005) investigated long-term changes in groundwater chemistry at the demonstration site and reported selected data up through July 2001. A main conclusion of the study was that after 6 years, in situ biodegradation was becoming the dominant process at the site for reducing mass flux of TCE across the site (as opposed to the process of "transpiration directly from the aquifer," the dominant process during the first 3 years after planting).

- Clinton, et al (2004) examined the uptake of groundwater versus surface water by the Eastern cottonwood tree at the site and concluded that this activity was variable depending on water availability and transpirational demand.

- Vroblesky et al (2004) examined tree cores from 100 trees and concluded that the presence of TCE and *c*DCE in tree cores can be indicators of subsurface contamination, and that within an individual tree species, higher groundwater TCE concentrations can produce higher tree core TCE concentrations.

1.5 STAKEHOLDER/END-USER ISSUES

Because tree-based phytoremediation processes can take years to become fully effective, long-term monitoring and evaluation were needed to demonstrate system effectiveness and better define phytoremediation mechanisms. Therefore, stakeholders must be confident that enough funds are available for long-term compliance monitoring to meet site-specific cleanup criteria (USEPA, 2003). However, before initiating a phytoremediation corrective action for shallow groundwater, it is imperative to determine if natural attenuation processes (i.e., biodegration, dispersion, sorption, or volatilization) are able to achieve site-specific remedial objectives within a comparatively reasonable time frame. If site-specific natural attenuation processes operating at

a site are capable of reducing mass, toxicity, mobility, or volume of halogenated hydrocarbons in the soil and groundwater, that site may not be a candidate for a phytoremediation intervention.

According to Harvey (2005), the extensive sampling conducted for this research "is not indicative for routine phyto approaches." Sufficient funds, sufficient land to plant, and time are essential to a successful phyto operation. Simply planting a few trees is not usually enough to alter either site hydraulic or geochemistry (Harvey, 2005).

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The short rotation woody crop groundwater treatment (SRWCGT) system employed at the Carswell Golf Course (CGC) falls within the broad emerging remediation technology class referred to as phytoremediation. Phytoremediation is best described as a solar-energy driven passive technique that is applicable for the remediation of sites having low to moderate levels of contaminants at shallow depths. Phytoremediation takes advantage of plants' nutrient utilization processes to take in water and nutrients through roots, transpire water through leaves, and act as a transformational system to metabolize organic compounds or absorb and accumulate inorganic compounds. Research has found that certain plants can be used to treat most classes of contaminants, including petroleum hydrocarbons, chlorinated solvents, pesticides, metals, radionuclides, explosives, and excess nutrients. In addition, plants have also shown a capacity to withstand relatively high concentrations of organic chemicals without the types of toxic effects experienced with bioremediation systems. In some cases, plants have demonstrated the ability to uptake and quickly convert chemicals to less toxic metabolites.

About 30 years ago the U.S. Department of Energy (DOE) embarked on a program to grow plants as a source of fiber and fuel in response to the oil embargoes of the early 1970s. As a result of this effort, an extensive body of public domain information was created on the physiology and development of short rotation woody crops (SRWCs). A SRWCGT system uses trees to control hydraulically the migration of contaminated groundwater and to enhance biologically the subsurface environment to optimize in situ reductive dechlorination of the chlorinated ethenes. The SRWCGT system is reported to be an "evolving" and adaptive process that adjusts to site conditions and increases its effectiveness over time (USEPA, 2003). Depending on the nature of contamination problems at a site and its particular hydrogeologic setting, plant species are selected based on their following characteristics:

- Growth rate and yield
- Evapotranspiration potential
- Production of degrading enzymes
- Depth of root zone
- Contaminant tolerance
- Bioaccumulation ability

Phytoremediation systems are typically applicable to sites having relatively shallow groundwater contaminated with organic compounds. The direct uptake of organics by trees has been found to be an efficient removal mechanism at sites contaminated at shallow depths with moderately hydrophobic organic chemicals (octanol-water partition coefficients, log K_{ow} = 1 to 3.5). Tree-based phytoremediation systems are applicable to sites having soil and groundwater contaminants consisting primarily of benzene, toluene, ethylbenzene and xylenes (BTEX); chlorinated organics; and short-chain aliphatic compounds (e.g., petrochemical sites, ammunition waste sites, fuel spills, chlorinated solvent plumes, landfill leachates, and agricultural chemicals) (USEPA, 2003).

2.2 PROCESS DESCRIPTION

SRWCGT can enhance in-situ biodegradation of chlorinated solvents (Harvey, 2005). Five specific processes have been associated with the phytoremediation treatment at the CGC. These processes and methods for quantifying their contributions are listed in Table 1.

Table 1. Phytoremediation Processes and Methods Used to Quantify Their Contributions.

Process and Theory of Operation	Methods for Quantifying
1. *Phytocontainment*—Transpiration from trees induces a cone of depression to contain contaminated groundwater. (Native or planted vegetation must transpire enough water from the soil or groundwater layer containing the pollutant to control transport or decrease contaminant mass).	Direct sapflow measurements Precipitation minus runoff of gauged watersheds Energy balance (e.g., Penman-Monteith equation) Eddy covariance (a.k.a. eddy correlation) Hydrologic models
2. *Phytostimulation*—Plant roots excrete compounds containing organic carbon, which serve as a food source for microorganisms (e.g., sugars, alcohols, and acids).	Analyze groundwater for breakdown products Measure spatial distribution of various microbial populations in the pore water
3. *Phytodegradation*—Natural substances in a tree's roots, stems, and leaves aid in degrading organics (e.g., trichloroethene [TCE]).	Analyze root, stem, and leaf samples for contaminants and their breakdown products.
4. *Phytovolatilization*—Multimedia transfer of contaminants from water or soil to the atmosphere (i.e., the plant's ability to remove organic compounds like TCE from the leaf surface once its traveled through the plant).	Analyze transpired vapors from trees (not conducted for the demonstration)
5. *Phytostabilization*—Plants bind contaminated soils in place, resulting in immobilization of toxic contaminants.	Sequential slug testing

Sources: USGS, 2004 and Vose et al, 2003.

Of the five processes listed in Table 1, phytocontainment was a primary objective of the demonstration (see Section 3.1). Phytocontainment is achieved via transpiration (the evaporative loss of water from a plant). Transpiration is used to determine current and future water usage. Water transport mechanisms move water from the soil zone to the stomata of the leaf where it is lost to the atmosphere. Transpired water can be derived from the near surface soils, and in the case of phreatophytic species such as Eastern cottonwoods, from the saturated zone (i.e., aquifer). The ability of phreatophytic species to seek and use contaminated groundwater is the basis of the SRWCGT system technology. The amount of water transpired by trees throughout their life cycle is an important factor in determining the effectiveness of the technology for containment and remediation of a contaminant plume. Transpiration rates can be used in conjunction with other site-specific characteristics (climate, soil type, and hydrology) to determine water use patterns and to help determine process effectiveness, including future performance (USEPA, 2003).

In addition to containment via transpiration SRWCGT systems have been theorized to enhance in situ biodegradation of chlorinated solvents. The biodegradation of chlorinated solvents begins in the saturated subsurface where native or anthropogenic carbon is used as an election donor, and dissolved oxygen (DO) is used first for the prime electron acceptor. Once DO is depleted, the process becomes anaerobic. Anaerobic microorganisms most often use available electron

acceptors in the following order: (1) nitrate, (2) ferric iron oxyhydroxide, (3) sulfate, and (4) carbon dioxide (CO_2). In the absence of DO and nitrate, chlorinated solvents compete with other electron acceptors and donors, especially sulfate and CO_2.

The anaerobic microbial utilization of the carbon source would drive reductive decholorination of the dissolved chlorinated solvent (e.g., TCE) in the aquifer (Wiedemeier et al, 1996). The dechlorination pathway for TCE is TCE -> *c*DCE + Cl -> VC + 2Cl -> ethene +3Cl. The efficiency of TCE degradation varies, depending on microbially mediated redox reactions (most efficient to least efficient—methanogenesis, sulfate reduction, iron (III) reduction, and oxidation).

2.3 PREVIOUS TESTING

To date few geochemical performance data have been available from field-scale phytoremediation sites to assist in design of phytoremediation projects. Specifically, questions remain as to the potential influence of vegetative biomass on groundwater geochemistry: Can trees or other plants provide a sustainable source of electron donors via leaf litter and root exudates and decay? How much vegetation is needed to influence geochemical changes? How long does it take before geochemical changes are observed in aerobic aquifers? Do geochemical influences fluctuate seasonally? Can year-round reducing conditions be achieved? (Eberts et al, 2005).

2.4 ADVANTAGES AND LIMITATIONS

2.4.1 Advantages

Tree-based phytoremediation systems are well suited for use at very large field sites where other methods of remediation are not cost effective or practical. They can exploit heterogeneous subsurface environments and fill a niche between monitored natural attenuation and engineered bioremediation systems (Eberts et al, 2005). They are best utilized at sites with low concentrations of contaminants where the remediation objectives are consistent with a long-term contaminant reduction strategy (USEPA, 2003). Where phyto potential is most applicable is with large aerobic plumes with dilute low concentration halogenated solvents (Harvey, 2005). However, they can also be used at sites with phytotoxic levels of organic contamination and posing acute exposure risks if a faster and more expensive ex situ technique is applied first. A tree-based phytoremediation system can thus serve as a final polishing step to close the site after other cleanup technologies have been used to treat the hot spots (Dietz and Schnoor, 2001). Tree-based phytoremediation systems have minimal site support requirements, typically requiring few utilities to operate. A hookup to a drip irrigation system may be needed to periodically supply water over the first few growing seasons when young trees are most susceptible to water stress problems. Depending on local regulations, nonpotable water from a contaminated aquifer might be used at no cost. This could also enhance groundwater treatment during the first few growing seasons when little remediation is expected. Electricity, needed to operate well pumps, can be provided by small generators. Monitoring equipment (e.g., soil moisture probes, pressure transducers, data loggers, and weather station) can be powered by batteries or solar panels (USEPA, 2003).

Until recently, most of what is known about phytoremediation was derived from laboratory and small-scale field studies. Phytoremediation approaches in general have received higher public acceptance than most conventional remedial options. Phytoremediation systems can be used along with or, in some cases, in place of intrusive mechanical cleanup methods. They can function with minimal maintenance once established, generate fewer air and water emissions, generate less secondary waste, and leave soil in place; and generally they are a fraction of the cost incurred for a mechanical treatment approach (USEPA, 2003).

2.4.2 Limitations

A tree-based phytoremediation treatment system can be land intensive, requiring enough clear space for the required number of trees to be grown in a given area to do the job (USEPA, 2003). The process is better suited for warmer climates, which are more conducive to the key process of transpiration. Optimal climate conditions for transpiration include high soil water availability, high solar radiation, high vapor pressure deficits, warm temperatures for extended periods, and high wind speed (Vose et al, 2003).

Since the process can take years to become fully effective, it may not be the most suitable remediation technique for sites that pose acute risks for human and other ecological receptors. Very high concentrations of organics may actually inhibit tree growth, thus limiting application of this technology at some sites or portions of sites. Other more costly treatment alternatives, such as excavation, landfilling, or incineration may be better to achieve cleanup standards quicker (Dietz and Schnoor, 2001). At Carswell, it took almost 3 years before the trees delivered enough dissolved organic carbon (DOC) to create iron-reducing conditions (Harvey, 2005).

Depending on the depth to groundwater, the length of growing season, and tree type, it may take two or more growing seasons before a tree-based phytoremediation system starts to exert a hydraulic effect on the contaminated aquifer. It may take even longer before microbial mediated reductive dechlorination becomes a viable mechanism (potentially more than 10 years to completely remediate a site). Actual removal and degradation of organics in contaminated matrices is likely limited by mass transfer; therefore, desorption and mass transport of chemicals from soil particles to the aqueous phase may become a rate-limiting step. Long-term monitoring and evaluation of such technologies is needed to demonstrate effectiveness and better define treatment mechanisms.

Contaminant to root contact, a function of root depth and mass, is generally a limiting factor for direct uptake of contaminants into the tree. This is not necessarily true for enhanced reductive dechlorination processes, however. While most phytoremediation systems are limited to the upper 3 meters (m) of the soil column, research and SITE Program experience suggests that hybrid poplar tree systems may be effective to depths greater than 8 m. Systems that utilize other tree species may be effective to even greater depths. Other plants such as alfalfa, willows, or even mesquite can achieve deep significant below-ground biomass without employing patented planting techniques (Harvey, 2005). To overcome these depth barriers, researchers and phytoremediation companies have developed and employed specialized (often proprietary) techniques that train the tree roots to penetrate to greater depths, or herd them into deeper contamination zones through the use of subsurface drip irrigation. Deeper zones of

contamination can possibly be treated through a process of pumping the contaminated groundwater to the surface and applying it to the plantations through drip irrigation.

Contamination too tightly bound to the organic portions of soil and root surfaces may also pose limitations on the effectiveness of this technology. Little if any documentation supports the process as a viable option in the remediation of highly lipophilic compounds such as polychlorinated biphenyls (PCB), which are generally so strongly bound to soil that they do not become bioavailable to either plants or microbes (USEPA, 2003). It is possible, however, that enhanced rhizospheric bioremediation may be capable of breaking down some PCB congeners (USEPA, 2003). Hydrophobic compounds ($\log K_{ow} > 3.5$), because of their octanol-water partition coefficients (K_{ow}), cannot be easily translocated within the tree or are simply unavailable to microorganisms in the rhizosphere. On the other hand, contaminants that are too water soluble ($\log K_{ow} < 1.0$) are not sufficiently sorbed to roots nor actively transported through plant membranes. These contaminants would simply pass through the roots unimpeded.

The fate of contaminants in tree tissue is not well documented. There is a potential that contaminants in tree tissue can present an ecological exposure threat by one or more of the following means (USEPA, 2003):

- Contaminants collected in leaves can be released as litter during fall or can accumulate in fuel wood or mulch.

- Ingestion of significant amounts of vegetation by organisms (caterpillars, rodents, birds, deer, etc.) may cause concern that harmful bioconcentration up the food chain is occurring; although this threat is more obvious and better understood for plants that extract or accumulate heavy metals and radionuclides.

- Contaminants or metabolites can be transferred from soil or groundwater to the atmosphere via evapotranspiration. This is a potential regulatory limiting factor.

Research to determine if organic contaminants simply pass through the trees and are released to the atmosphere through leaf stomata during evapotranspiration has produced mixed results and is not close to being quantified. Transpiration of TCE to the atmosphere has been measured (Neuman et al, 1996), but little information is available that indicates any release of more toxic daughter products i.e., vinyl chloride (VC). The same researcher has shown that a series of aerobic transformations occur whereby some TCE is transformed to trichloroethanol, trichloroacetic acid, and dichloroacetic acid by hybrid poplar trees (USEPA, 2003).

Natural causes such as the following can adversely impact or damage SRWC plantations:

- High velocity winds can cause mechanical stresses (e.g., hybrid poplars deep planted in Maryland with engineering controls to inhibit shallow lateral roots had almost a 20% incidence of toppling in the wake of Hurricane Floyd (Compton, 2003). However, trees planted in wells without lateral roots are more likely to tip over under a wind load (Harvey, 2005).

- Biotic stressors (i.e., insects, fungi, viruses, bacteria, and gnawing animals) can threaten the success and reduce the productivity of poplar and willow SRWCs. Many readily available poplar trees are extremely susceptible to certain insect pests and diseases (Ostry et al, 1989). Disease susceptibility among poplar clones is usually expressed by the second growing season (Hansen, 2003) (USEPA, 2003). Poplars are an important food for moose, beavers, white-tailed deer, and many bird species. Beavers also use poplars to construct dams and lodges. Beavers at the demonstration site have been an annual concern since 1996. Braun et al, 2004 reported that up through the start of 2003 49% of the trees in the caliper plantation were either stunted by beaver activity (40%) or altered by human activities (9%).

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

One primary objective and seven secondary objectives were established to evaluate the effectiveness of the SRWCGT system at the CGC. Cost and performance data was also used to determine the applicability and limitations of the technology to similar sites with similar contaminant profiles. The project objectives are discussed in the following subsections. The methods used for their determination are presented in Table 2.

3.1.1 Primary Objective

The primary objective of the SRWCGT system at the CGC site focused on localized hydraulic containment and treatment of a groundwater TCE plume. The two goals comprising the primary objective were to:

- Achieve 30% reduction in mass of TCE in the aquifer that is transported across the downgradient end of the site during the second growing season, relative to baseline TCE mass flux calculations

- Achieve 50% reduction in mass of TCE in the aquifer that is transported across the downgradient end of the site during the third growing season, relative to baseline TCE mass flux calculations.

It was hypothesized that the trees' root systems would remove contaminated water from the aquifer, then biologically alter the TCE within the trees or transpire and volatilize the TCE into the atmosphere. The trees were to also promote microbially mediated reductive dechlorination of dissolved TCE within the aquifer. The mass of TCE transported in the aquifer across the downgradient end of the plantations at a given time was determined by multiplying the volumetric flux of groundwater across the downgradient end of the site by the average TCE concentration in a row of three wells located immediately downgradient of the Caliper Tree Plantation (identified by the last three digits 526, 527, and 528 in Figure 1). Volumetric flux of groundwater was calculated for each of three events per year (baseline, peak growing season, late growing season) for 2 years, according to the equation below.

$$Q = -KiA$$

Where: Q is the volumetric flux of groundwater as calculated according to Darcy's Law;

K	=	Hydraulic conductivity of aquifer;
i	=	Hydraulic gradient in aquifer across downgradient end of planted area; and
A	=	Cross-sectional area of aquifer along downgradient end of the planted area.

The following assumptions applied to the calculations:

- A constant horizontal-hydraulic conductivity value of 6 meters per day (m/d) represented the study area geometric mean.

- An aquifer width of 70 m (approximate length of tree plantations) was used in volumetric-flux calculations.

- The hydraulic gradient across the downgradient end of the plantations was calculated at selected times using groundwater elevation data from two monitoring wells that did not reflect increases in the hydraulic gradient across the upgradient end of the site (Well 522, located between the tree stands near the center of the planted area, and Well 529, downgradient and outside the influence of the trees). A potentiometric surface map, corresponding to each selected time, was used to verify that changes in hydraulic gradient were due to the influence of the trees rather than to changes in direction of groundwater flow.

- Saturated zone thickness at the selected times was calculated from the average thickness of the aquifer in the monitoring wells immediately downgradient of the tree plots (wells 526, 527, and 528). Saturated thickness in each of these three wells was first normalized to wells in the surrounding area to account for temporal changes in the saturated thickness of the aquifer unrelated to the planted trees (i.e., water-level data for these wells were adjusted by an amount equal to the difference between the water level at the selected time and the baseline water level in wells outside the influence of the planted trees). Baseline conditions were represented by the most comprehensive set of water-level and groundwater chemistry data collected the period before the tree roots reached the water table in November 1996.

$$M_f = Q(C)$$

The mass flux across the downgradient end of the planted area was subsequently calculated for the various events (baseline, peak growing season, late growing season) according to the following formula:

Where: Q is the volumetric flux of groundwater; and
C = average TCE concentration in wells 526, 527, and 528 (immediately downgradient of the planted area)

The following formula was then used to calculate the percent change in the mass flux of TCE at selected times that can be attributed to the planted trees:

$$\Delta M_f(event\ x) = \frac{M_f(baseline) - M_f(event\ x)}{M_f(baseline)} (100)$$

Where: Event x is peak of the1997, 1998, or 1999 growing season (i.e., late June or beginning of July); or
late in the1997 or 1998 growing season (i.e., end of September or beginning of October).

3.1.2 Secondary Objectives

Secondary objectives were additional tasks that were to elucidate the biological, hydrological, and biochemical processes that contribute to the effectiveness of a SRWCGT system on shallow TCE-contaminated groundwater. Also, since a SRWCGT system can take several years to become fully effective, much of the data associated with the secondary objectives were collected to build predictive models to estimate future performance. Measurements were primarily related to tree physiology (tree growth, tree transpiration, contaminant translocation) and aquifer characteristics (hydraulic, geochemical, microbiological). The tasks comprising secondary objectives included the following: (1) Determine tree growth and root biomass; (2) Analyze tree transpiration rates to determine current and future water usage; (3) Analyze hydrologic effects of tree transpiration on the contaminated aquifer; (4) Analyze contaminant uptake into plant organ systems; (5) Evaluate geochemical indices of subsurface oxidation-reduction processes; (6) Evaluate microbial contributions to reductive dechlorination; and (7) Collect data to determine implementation and operation costs for the technology.

3.1.3 Objectives of Follow-On Studies

There was no field evidence from the 3-year demonstration study that suggested complete in situ biodegradation of TCE and its daughter products could be achieved at the CGC (USEPA, 2003). Partly for this reason, follow-on studies were conducted following the 3-year demonstration. Results of these studies are provided in Section 4.3, Data Assessment. The objectives of each study are briefly summarized in the following paragraphs.

1) Evaluate Phytoremediation-Induced Geochemical Changes in the TCE Plume

Groundwater monitoring at the demonstration site for volatile organic compounds (VOCs) was continued through the sixth growing season (2002) to evaluate phytoremediation-induced geochemical changes in the TCE plume. Emphasis was placed on the relation of biodegradation rates to the age of the tree plantations and associated increases in vegetative biomass. Specifically examined were changes in redox conditions resulting from increases in DOC associated with the planting of Eastern cottonwood trees and accompanying changes in the in situ reductive dechlorination of TCE (Eberts et al, 2005). Monitoring of groundwater redox conditions is ongoing (Braun, 2005).

2) Evaluate Core Tree Trunks to Determine the Presence of Chlorinated Ethenes in Groundwater

Between 1998 and 2000 a tree coring study was conducted at three separate Department of Defense (DoD) sites, one being the CGC. The study focused on applying tree coring to indicate the presence of chlorinated ethenes in groundwater, using a relatively quick and inexpensive technique for plume delineation and siting of groundwater monitoring wells. The entire study

examined more than 100 trees. At the CGC site, cores were collected from a total of 29 mature trees representing 10 different species (Vroblesky et al, 2004).

3) Determine Relative Uptake of Groundwater vs. Surface Water by Populus deltoides During Phytoremediation

This main objective of this July 2000 study was to examine relative uptake of surface water versus groundwater by mature trees to determine the relative contribution of groundwater to plant transpirational water use. This information was needed to accurately estimate the amount of contaminant the trees extracted from the groundwater versus contamination extracted in soil water (i.e., vadose zone). There were three types of measurements used to meet the objective: (1) isotope measurements in irrigation versus groundwater, and in tree sap; (2) sapflow measurements used to estimate tree transpiration rates; and (3) TCE concentrations in xylem sap.

3.2 SELECTION OF TEST SITE

Plumes of chlorinated solvents can naturally attenuate, but almost 80% of the time they do not due to the lack of electron donors (Chapelle, 2000). The CGC is typical of DoD sites having very large unattenuated plumes due to the lack of adequate amounts of native and/or anthropogenic carbon and DO levels greater than 1.0 milligrams per liter (mg/L). For this reason and for its geographical location, type of contamination, and depth of contamination, the CGC site was selected to demonstrate the SRWCGT system. Specifically, the site exhibited the following characteristics:

- Type-3 conditions (i.e., DO levels >1 mg/L and lack of carbon sources prevented reductive dechlorination of chlorinated compounds). Eastern cottonwood trees potentially can add enough natural organic carbon to the groundwater to support in situ microbial reductive dechlorination (Eberts et al, 2003).

- The groundwater at the site is shallow and thus accessible to trees soon after planting.

- An ample area, clear of obstructions, was available for siting plantations (i.e., the technology is well suited for use at very large field sites where other methods of remediation are not cost effective or practical).

- The site allowed for long-term field-scale monitoring and evaluation (Eberts et al, 2003).

- Previously installed wells were available for monitoring the treatment system (water levels in wells provide a direct means for assessing groundwater uptake by the trees).

In addition, drought-resistant trees were available from local sources. Phreatophytic trees are rapid growing and, in terms of subsurface biomass and transpiration capacity, offer unique opportunities for phytoremediation. When water becomes limited, phreatophytes are more resistant to wilting than shallow rooted plants. Trees have the most massive root system of all plants, and their root systems are capable of penetrating several meters below the surface

(Stomp, 1993). Examples of phreatophytic trees are willows, cottonwoods (poplars), salt cedar, and mesquite (Fetter, 1988).

3.3 SITE CHARACTERISTICS

The site selected for the demonstration was an approximate 70-m-wide portion of a TCE plume on the north side of the CGC (USEPA, 2003). This small section is a portion of a central lobe of a large groundwater TCE plume that originates upgradiant of the CGC at the former Carswell Air Force Base (Plant 4). Historically, the manufacturing processes at Plant 4 generated an estimated 5,500 to 6,000 tons of waste per year, including waste solvents, oils, fuels, paint residues, and miscellaneous spent chemicals (USEPA, 2003). TCE is believed to have leaked from degreasing tanks in the assembly building at Plant 4 and entered the underlying alluvial aquifer. An Installation Restoration Program (IRP) was initiated with a Phase I records search in 1984 (CH2M Hill, 1984). The U.S. Army Corps of Engineers (USACE) was retained in June 1985 to further delineate groundwater conditions in the Plant 4 East Parking Lot area; six monitoring wells were installed as part of this investigation (USACE, 1986). Groundwater sampling in the East Parking Lot area continues for the purpose of monitoring the TCE plume, which has migrated in an easterly-southeasterly direction under the East Parking Lot towards the CGC. The plume extends toward the east with its major branch following a paleochannel under the flight lines to the south of the CGC. This finger of the plume is being remediated with a pump-and-treat system. Another branch of the plume appears to follow a paleochannel to the north of the CGC. Data indicate that TCE may have entered the CGC area along an additional finger of the plume (USEPA, 2003). Table 2 presents climate and hydrogeological characteristics of the CGC.

Table 2. Summary of Site Climate and Hydrogeology.

Climate	Hydrogeology and Aquifer Characteristics
Climate type: Subhumid Temperature: 18.6 ºC (65.5 ºF)* Precipitation: 80 cm/yr*	Surface soils (0-200 cm): Silty-clay to clay loam with depth Depth to groundwater: 2.0-3.4 m (7-11 feet) Groundwater flow direction: Northwest to southeast Aquifer lithology: Clayey sands and gravel Aquifer saturated thickness: 0.5–1.5 m (1.5–5 feet) Aquifer total thickness: 6–15 feet Aquifer porosity: 25% Horizontal hydraulic conductivity range: 1–30 m/d (geometric mean = 0.36 m/d) Average hydraulic gradient: just over 2%

* Values are annual averages
Sources: Eberts et al, 2003; EPA, 2003; Vroblesky et al, 2004; Clinton et al, 2004; USDA, 1981.

3.4 PHYSICAL SET-UP AND OPERATION

The Eastern cottonwood tree (*Populus deltoides*) was selected for this study on the basis of a literature review and discussions with the Texas Forest Service, the National Resources Conservation Service, and the U.S. Forest Service (FS) Hardwood Laboratory. The Eastern cottonwood is native as far south and west as Texas, which contributed to the decision to select these trees for the site (Southern Forest Nursery Management Cooperative, accessed

December 19, 2000, at www.forestry.auburn.edu/sfnmc/class/cotton.html). Being phreatophytes, poplars are an especially attractive option in hot, dry, and windy environments in the southwestern United States (Vose et al, 2003). In summary, cottonwoods were selected because they have the following features:

- Rapid growth and easy to regenerate

- High transpiration rates and phreatophytic properties, which allow rapid transpiration of water from a saturated zone and maximize below-ground biomass (an important factor in establishing biogeochemical reductive pathways)

- Tolerance to the contaminants of concern

- Natural occurrence at the selected site making them readily available

- Longevity of 40 to 100 years (USEPA, 2003).

Based on an estimated transpiration rate of 100 liters day^{-1} (L day^{-1}) per hybrid poplar tree occupying 4 m^2 of ground (Stomp, 1993), it was determined that a minimum of 100 trees would need to be planted at the demonstration site. However, since this estimate was for optimal conditions (field conditions at the site were not expected to always be optimal), 662 trees were actually planted. It was also expected that some trees would be lost due to natural attrition caused by poor planting, disease, and insects; and it was anticipated that some transpired water would be derived from intercepted precipitation or soil moisture, or from groundwater released from storage rather than from groundwater flowing into the site across the upgradient end (USEPA, 2003).

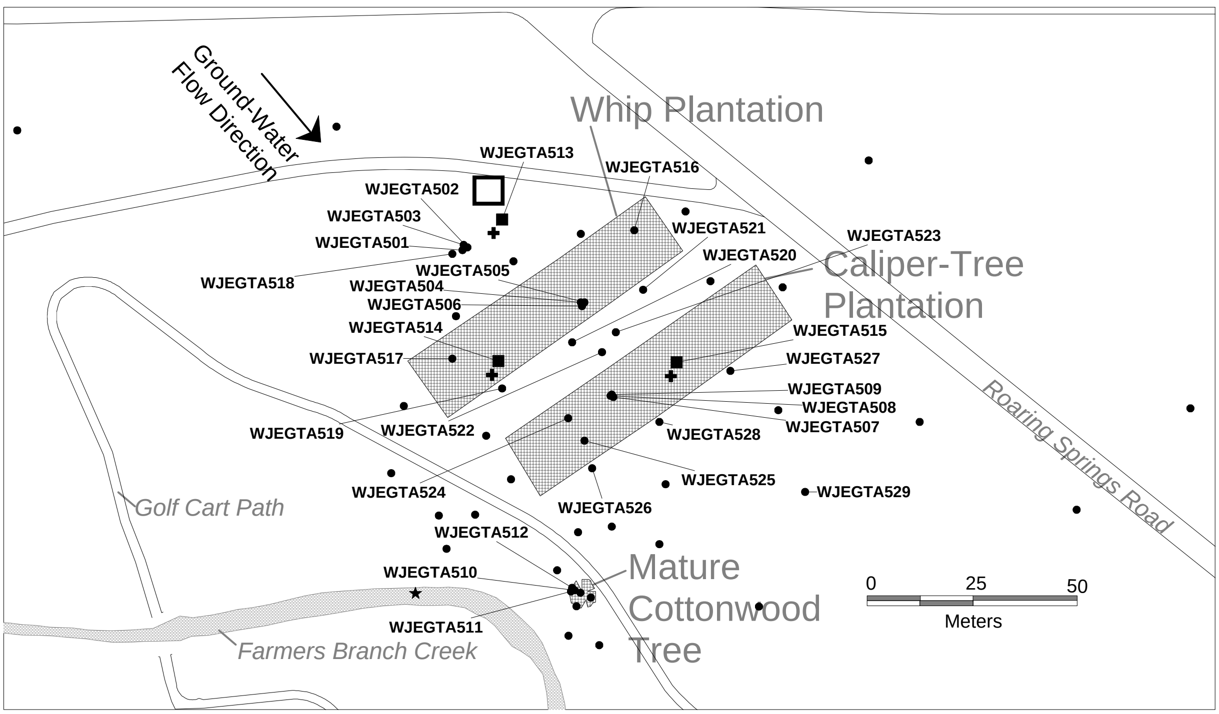
Two sizes of trees were selected for planting ("whips" and "caliper trees") so that differences in rate of growth, contaminant reductions, and cost based on planting strategy could be compared. Two approximate 15 by 75 m rectangular-shaped plantations were designed, one planted with seven rows of whips (438 total) and the other planted with seven rows of caliper trees (224 total). Both plantations are oriented generally perpendicular to groundwater flow direction and span the most concentrated portion of the underlying TCE-groundwater plume (Figure 1). Characteristics of the trees planted are presented in Table 3.

The soil preparation and planting method used for the demonstration began with trenching seven rows in each of the proposed plantations to a depth of 1 m. The whips or caliper trees were placed within the trenched rows along with irrigation lines. An agronomic assessment identified macronutrients and micronutrients and verified the presence or absence of hard pans. The need for fertilizer was determined from (1) the soil characteristics that were identified through sampling and analyses and (2) from discussions with the Texas Forest Service, Tarrant County Agricultural Extension Service, and the Texas A&M Horticulture Department. A handful of slow release Osmacote 14-14-14 fertilizer was applied around each whip and caliper tree. After planting, fabric mulch and 10 cm of landscape mulch were placed along each of the planted rows to reduce weed competition. This was especially important for the newly planted whips.

The drip irrigation system was used to supplement precipitation for the first two growing seasons. The trees were watered liberally during this time to encourage deep root development. Data from a precipitation gage at the site were used to help make irrigation decisions. Because the roots were expected to intercept percolating irrigation water (Licht and Madison, 1994), irrigation was not considered to be an additional source of water to the aquifer.

3.5 SAMPLING AND MONITORING PROCEDURES

Because SRWCGT system processes require extended time frames to develop (USEPA, 2003), the monitoring system had to be designed to measure small incremental changes in site conditions over time. The monitoring strategy for the demonstration was more extensive than would be required for a typical SRWCGT system project due to the research nature of the study. Data collected from this intensive monitoring program were used to determine how well the system behaved over time and to develop models to predict future system performance. The following monitoring stations were employed in the study:



EXPLANATION

• MONITORING WELL – Well number indicates well sampled throughout the entire demonstration	★ STREAM-STAGE GAGE
■ MONITORING WELL WITH WATER LEVEL RECORDER	✚ TENSIOMETER NEST
	❑ WEATHER STATION

Figure 1. Site Layout for the SRWCGT System.

Table 3. Tree Characteristics and Planting Specifications.

<table>
<tr><th colspan="3">Tree Characteristics</th><th colspan="6">Planting Specifications</th></tr>
<tr><th>Tree Type [1]</th><th>Varieties Planted [2]</th><th>Source</th><th># of Trees Planted</th><th>Planted Size</th><th>Depth</th><th>Row Spacing</th><th>Tree Spacing</th><th>Added Amendments</th></tr>
<tr><td>Whips</td><td>S7C1, S7C2, S7C4, S7C8, S7C13, S7C15, S7C20, S7C21, S13C15, S13C20, KEN8</td><td>Texas Forest Service—Alto, Texas</td><td>438 (7 rows)</td><td>~0.5 m tall</td><td>1 m</td><td>2.4 m</td><td>1.2 m</td><td rowspan="2">- Osmacote™ 14-14-14 fertilizer
- Fabric mulch
- Landscape mulch (10 cm)</td></tr>
<tr><td>Calipers</td><td>Sioux Land</td><td>Gandy Nursery —Ben Wheeler, Texas</td><td>224 (7 rows)</td><td>~0.5 m tall</td><td>1 m</td><td>2.4 m</td><td>2.4 m</td></tr>
</table>

[1] Whips—sections of 1 year old stems harvested from branches during the dormant season; Calipers—saplings just over 2 m tall when planted.
[2] Whips included a mixture of the Eastern cottonwood clones listed.

- Sixty-seven wells installed upgradient, within, downgradient, and surrounding the demonstration site, including the area under the mature cottonwood tree near the site

- Continuous water level recorders installed in three monitoring wells, including one upgradient of the tree plantations and two within the planted area

- Nine tensiometers installed upgradient or within the tree plantations

- A weather station installed to collect site-specific climate data

- A stream gage installed on a creek adjacent to the site to record stream stage

- Collars and/or probes installed in selected trees to measure sapflow periodically during the growing season.

The location of most of these monitoring points with respect to the tree plantations is shown in Figure 1. A number of wells are not shown because they are outside the area depicted in the figure. These wells were used to collect groundwater level data surrounding the site for use in calibrating a groundwater-flow model of the area that could be used to help predict out-year performance of the SRWCGT system (USEPA, 2003).

Unfiltered groundwater samples were collected by a peristaltic pump from wells constructed of PVC casings and screens. Most sampled wells are screened across the entire saturated thickness of the aquifer; however, some nests of wells with shorter screen lengths were included to observe vertical patterns in TCE concentrations within the aquifer. Screen lengths range from 0.1 to 1.2 m. Wells were pumped for at least 30 minutes before sampling, and at least 3 casing volumes were purged from each well before samples were collected. The SITE Program employed micropurge techniques.

3.6 MEASUREMENTS AND ANALYTICAL PROCEDURES

For the 3-year demonstration, most of the sample analyses were conducted at an Environmental Protection Agency (EPA) in-house laboratory. However, after the demonstration in 1998, additional groundwater samples were field-analyzed due to resource constraints. Table 4 presents a summary of the measurements and analytical procedures used during the 3-year demonstration and the associated follow-on studies conducted at the CGC.

Table 4. Summary of Methods and Techniques Used for the Demonstration and Associated Studies.

Objective	Measurement Category	Measurement	Quantity	Frequency	Method
Primary Objective	- Hydrogeology - Contaminant mass flux	- Continuous water levels - VOCs in groundwater	3 wells (526, 527, 528; all immediately downgradient and outside influence of trees	- 6 occasions - 4 occasions Baseline Peak second season Peak third season Late third season	- Data logger - VOCs analyzed by EPA in-house laboratory via SW-846 8260B
Secondary Objective 1	Above-ground biomass	- Trunk diameter - Tree height - Canopy diameter	103 (52 whips, 51 caliper trees)	6 occasions— Dec. ’96, May ’97, July ’97, Oct. ’97, June ’98, Oct. ’98	- Caliper - Grad. 2′x4′ wood - Grad. 2′x4′ wood
	Below-ground biomass	Root system	8 (4 whips, 4 caliper trees)	Once (Sept. ’97)	Down hole root camera
Secondary Objective 2	- Transpiration rates - Climate data	- Sapflow - Leaf conductance - Leaf water potential [1]	14-16 trees	- May thru Oct. ’97 - May thru Oct. ’98	- Dynagage™ tree collar, or Thermal dissipation probes - Weather station
Secondary Objective 3	Hydrogeology	- Seasonal water levels - Continuous water levels - Creek stage - Hydraulic conductivity - Aquifer porosity	62 wells 3 wells - 1 gauge point - 11 wells - 11 sample locations	9 occasions— (Nov.’96–June ’99) - Every 15 min. - Every 15 min. (’98) - Once - Once	- Electric tape - Data logger - Slug tests and lab-analyzed cores
Secondary Objective 4	VOCs in plant organs	- VOCs in roots, stems, and leaves	12 trees (5 whips, 5 caliper trees, 1 mature cottonwood, and 1 mature mesquite tree)	5 occasions— (Oct. ’96, July ’97, Oct. ’97, June ’98, October ’98)	Based on EPA method 6233 – Disinfection By-Products: haloacetic acids and trichlorophenol
	Dehalogenase activity	TCE in leaves	7 trees [2]	September 1998	
Secondary Objective 5	- Contaminant distribution - Indices of redox conditions	- VOCs, DOC, methane, sulfide, ferrous, and total iron, DO, and dissolved hydrogen in groundwater -TOC and pH in soil	21 wells 5 upgradient wells 9 plantation wells 4 downgradient wells 3 wells @ mature tree	5 occasions— (Dec. ’96, May ’97, July ’97, July ’98, Sept. ’98)	- VOCs analyzed by EPA in-house laboratory via SW-846 8260B - Standard methods
Secondary Objective 6	Microbial survey	Soil and groundwater	13 locations	Twice (February and June ’98)	five-tube most probable number (MPN) analysis [4]

Table 4. Summary of Methods and Techniques Used for the Demonstration and Associated Studies. (continued)

Objective	Measurement Category	Measurement	Quantity	Frequency	Method
Associated/ Extended Studies (1998-2002)	VOCs in plant organs	VOCs in tree cores	29 trees representing 10 species in surrounding area [3]	1998–2000	Increment borer
	Transpiration rates	Sapflow	Two mature cottonwood trees growing over delineated plumes of TCE and *c*DCE	Continuously from July 18 through July 22, 2000	Dynagage™ tree collar, or thermal dissipation probes
	Contaminant distribution	VOCs in groundwater	36-39 wells	6 times from January 1999 through July 2002	Photovac 10S50 Field GC/STL[5]
	Dissolved gases	Hydrogen gas (H_2), CO_2, methane (CH_4), alkalinity, specific conductance			"Gas stripping method"[6]
	Supplemental parameters	Nitrate, sulfate, sulfide, total and ferrous iron, dissolved oxygen			Colorimetric methods[7]

[1] Both "pre-dawn" and "mid-day" measurements collected.
[2] The 7 trees included a cottonwood whip, cottonwood caliper, cedar, hackberry, oak, willow, and mesquite.
[3] The 29 trees and 10 species included 12 eastern cottonwoods, six oaks, two live oak, three cedars, two willows, one hackberry, one pecan, one pine, one American elm, one unidentified species of elm, and one unidentified species thought to be a member of the *Sapotaceae* family (Vroblesky et al, 2004).
[4] Enumerations included aerobes, denitrifiers, fermenters, iron reducers, sulfate reducers, total methanogens, acetate-utilizing methanogens, formate-utilizing methanogens, and hydrogen-utilizing methanogens.
[5] Measurements were conducted in the field prior to January 2000. Field instrument was calibrated for TCE, *c*DCE, and VC. After 2000, samples were sent to Severn Trent Laboratories (STL) in Arvada, Colorado.
[6] H_2 analyzed by a reduction gas analyzer; CO_2 and CH_4 analyzed by an MTI dual-column gas chromatograph (GC)/thermal conductivity detector.
[7] Various colorimetric methods were used; DO measured by indigo carmine (Gilbert et al, 1982), nitrate measured by cadmium reduction (HACH Co, 1989), total iron measured by FerroVer (HACH Co, 1989), ferrous iron measured by 1,10 phenanthroline (APHA, 1992), sulfate measured by SulfaVer4 (APHA, 1992), and sulfide measured by methylene blue (USEPA, 1979).

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

This section presents selected performance data obtained during the 3-year demonstration of the SRWCGT system installed at the CGC site. The data selected for inclusion is more important to evaluating and attaining the demonstration objectives. References are provided for other data collected during the demonstration and during follow-on studies.

4.1.1 TCE Mass Flux

Table 5 presents the results of the calculations used to evaluate the primary objective goals described in the equations presented in Section 3. The SRWCGT system did not achieve the mass flux reductions of 30% and 50% for the second and third growing seasons, respectively. The TCE mass flux was actually up 8% during the peak of the second growing season, compared to baseline conditions. The planted trees reduced the outward flux of groundwater by 5% during the peak of the second season but TCE concentrations in the row of wells immediately downgradient of the trees were higher, resulting in the increase in TCE mass flux. These data suggest that the mass flux of TCE out of the planted area during the peak of the second season would have been even greater in the absence of the hydraulic influence of the trees. The TCE mass flux during the third growing season was down 11% at the peak of the season and down 8% near the end of the season, compared to baseline conditions. Concentrations of TCE during the third season in the row of downgradient wells were similar to baseline concentrations. The reduction in TCE mass flux is primarily attributed to a reduction in the volumetric flux of groundwater out of the site. The flux of groundwater out of the site during the peak of the fourth growing season was 8% less than at baseline. Groundwater was not sampled for TCE concentrations at this time. Variations in climatic conditions are the likely explanation for the differences in the outward flux of groundwater between the third and fourth seasons. In general, these data reveal that the SRWCGT system had begun influencing contaminant mass moving through the site during the 3-year demonstration.

4.1.2 Tree Growth Rates and Root Biomass

Overall, both plantations significantly increased in all physical parameters measured over the course of the study. The 52 whips and 51 caliper trees were measured for trunk diameter, tree height, and canopy diameter in December 1996, May 1997, July 1997, October 1997, June 1998, and October 1998 by the SITE Program. Figures 2, 3, and 4 graphically depict the physical changes in the whip and caliper tree plantations over time. Two of the 52 whips and three of the 51 caliper trees did not survive to the end of the study and other plantation trees were temporarily stunted by beaver activity during the study. Trunk diameters in both plantations increased over time; 1.41 cm to 5.13 cm for the whips, and 3.83 to 8.12 cm for the caliper trees. Tree height also significantly increased for both plantations. In December of 1996, tree height for the whips averaged 2.27 m and 3.77 m for the caliper trees. In September 1998, average tree height for the whips was 5.52 m and 6.64 m for the caliper trees. Although the caliper trees were taller during the first growing season, the whips were able to approach the height of the caliper trees by the end of the third growing season.

Table 5. Summary of Primary Objective Results.

Measurement	Measurement Event [e]					
	Baseline (1996)	Peak 2nd Season (1997)	Late 2nd Season (1997)	Peak 3rd Season (1998)	Late 3rd Season (1998)	Peak 4th Season (1999)
Hydraulic gradient across downgradient end of planted area [a]	0.0159	0.0154	0.0157	0.0143	0.0150	0.0153
Cross sectional area along downgradient end of planted area [b] (m^2)	84	82	83	82	83	81
Volumetric flux of groundwater across downgradient end of planted area [c] (m^3/d)	8.0	7.6	7.8	7.0	7.5	7.4
Change in volumetric flux across downgradient end of planted area attributed to planted trees (%)	---	- 5%	- 2%	- 12%	- 6%	- 8%
Average TCE concentration (µg /L) [d]	469	535	---	483	473	---
Mass flux of TCE across downgradient end of planted area (g/d)	3.8	4.1	---	3.4	3.5	---
Change in mass flux of TCE across downgradient end of planted area attributed to planted trees (%)	---	8%	---	-11%	-8%	---

[a] Gradient calculated between monitoring wells 522 and 529.

[b] An aquifer width of 70 m was used for the aquifer cross-sectional area calculations; aquifer thickness was the average of the saturated thickness in wells 526, 527, and 528 normalized to wells from the surrounding area to account for seasonal water table fluctuations unrelated to the planted trees.

[c] A horizontal hydraulic conductivity of 6 m/d was used for the volumetric flux calculations. This is the geometric mean of the hydraulic conductivity values determined for the study area.

[d] TCE concentration is the average in wells 526, 527 and 528.

[e] Peak growing season is the end of June or beginning of July. Late growing season is the end of September or beginning of October.

--- Data not collected or not calculated.

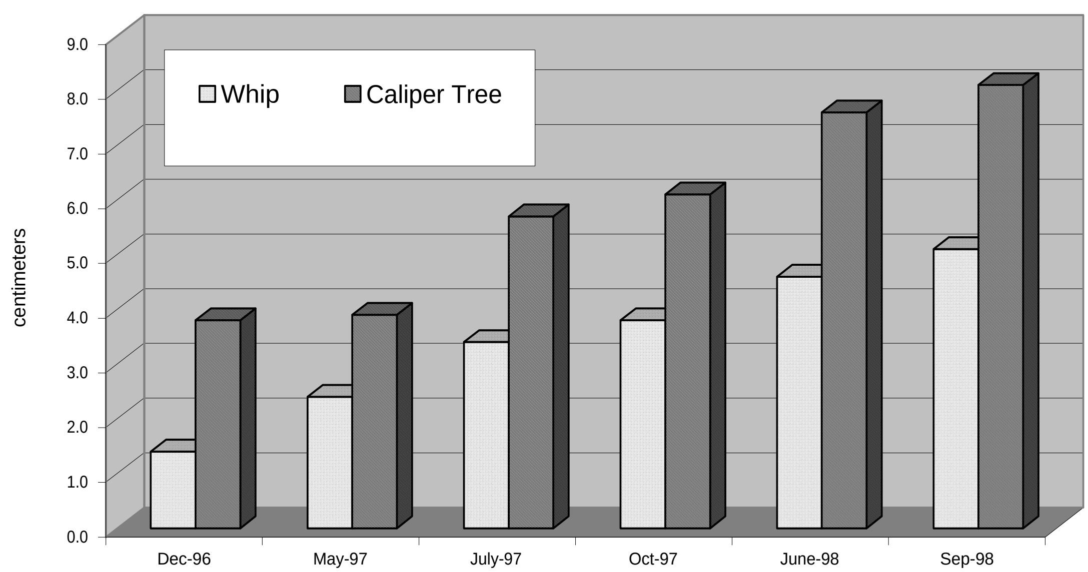


Figure 2. Trunk Diameter over Time.

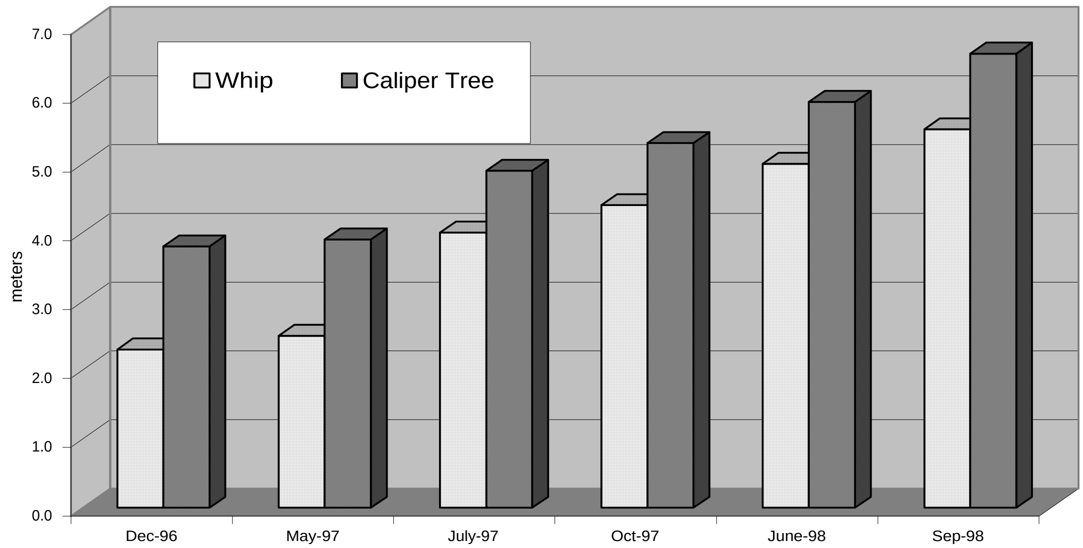


Figure 3. Tree Height over Time.

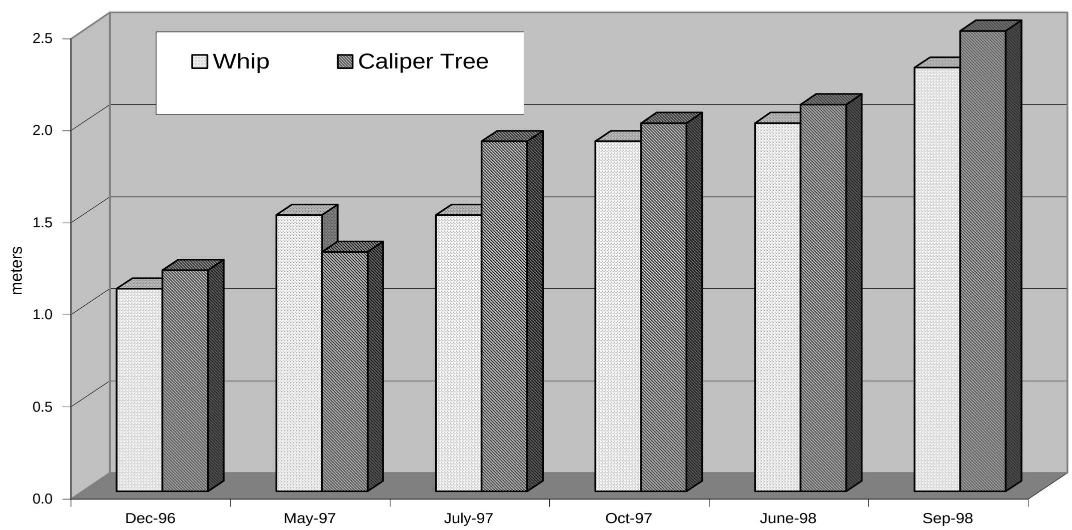


Figure 4. Canopy Diameter over Time.

Both the whips and caliper tree canopy diameter increased over time, with minor observable differences between the plantations. Whips were planted approximately 1.25 m apart. The average canopy diameter for whips at the end of September 1998 (end of the third growing season) was 2.32 m. The whip plantation was approaching canopy closure at this time. Caliper trees were planted approximately 2.50 m apart. The average canopy diameter for caliper trees in September of 1998 was 2.52 m. The caliper tree plantation was not approaching canopy closure at this time. The observed differences between whips and calipers over time were reported to be due as much to inherent genotype differences as to their different modes of establishment.

Root biomass and extent were examined for both plantations in September 1997, at which time the roots of both whips and caliper trees had reached the water table (275 cm for whips and 225 cm for caliper trees) (USEPA, 2003). The depth distribution of the roots was quite similar (Figure 5), indicating that the more expensive planting costs of the caliper trees did not appear to impart any substantial benefit with regard to root depth and biomass. Four trees from each plantation were evaluated for fine root biomass and length, coarse root biomass, and root distribution. Differences in the fine root biomass between the plantations were not statistically significant: 288 g m^2 for whips versus 273 g m^2 for caliper trees in the < 0.5 mm range; 30 g m^2 for whips versus 36 g m^2 for caliper trees in the 0.5 to 1.0 mm range; and 60 g m^2 for whips versus 91 g m^2 for caliper trees in the 1.0 to 3.0 mm range. Fine root length density in the upper 30 cm of soil was statistically greater in caliper trees as compared to whips (8,942 m m^2 versus 7,109 m m^2). Coarse root mass was significantly greater in caliper trees in the 3.0 to 10 mm range; 458 g tree-1 versus 240 g tree-1. Although the coarse root mass in the > 10 mm range was also greater in caliper trees than in whips, the difference in this range was not statistically significant. Details of this root study can be found in a report entitled, "Root Biomass and Extent in Populus Plantations Planted for Phytoremediation Purposes" (Hendrick, 1998).

4.1.3 Tree Transpiration Rates

Transpiration was measured on a statistical sampling of whips and caliper trees in May, June, July, August, and October of 1997 and on six mature trees in the vicinity of the study area in May, July, and September of 1998. Sapflow data were used to (1) compare transpiration rates for the two planting strategies (whips versus caliper trees), (2) investigate variability over the growing season, and (3) determine stand-level water usage over the entire growing season. Data from the mature trees were used to estimate upper-bound levels of transpiration that may be attainable by the SRWCGT system in the future. The transpiration measurements are summarized in a report "Leaf Water Relations and Sapflow in Eastern Cottonwood Trees Planted for Phytoremediation of a Groundwater Pollutant" (Vose et al, 2000). Table 6 summarizes the plantation tree transpiration measurements for the study.

Each plantation measures approximately 75 by 15 m, or 0.1125 hectares. This value was used to estimate the total average daily transpiration values in Table 6. Those values correlate with an estimated loss of water through transpiration from the study area of approximately 3,600 L day^{-1} (950 gallons per day [gal. day^{-1}]) during the second growing season. Total estimated growing season transpiration for the second season was estimated to be approximately 25 cm, approximately one-third to one-half the amount of transpiration for mature hardwood forests in other regions of the United States (Vose and Swank, 1992).

Table 6. Summary of Plantation Tree Transpiration Measurements.

Measurement (across 2nd Growing Season)	Plantation Tree Type	
	Whips	Caliper Trees
Average seasonal sapflow kilograms per hour per tree ($kg\ hr^{-1}\ tree^{-1}$) [a]	0.34	0.61
Average seasonal sapflow kilograms per square centimeter per hour ($kg\ cm^{-2}\ hr^{-1}$) [b]	0.033	0.027
Sapflow average across second growing season kilograms per hectare per day ($kg\ ha^{-1}\ day^{-1}$)	15,560	16,637
Mean total daily transpiration range ($kg\ tree^{-1}\ day^{-1}$) [c]	9.2 – 1.6	14.7 – 0.92
Mean total daily transpiration range gallons per tree per day ($gal.\ tree^{-1}\ day^{-1}$) [c]	2.4 – 0.42	3.89 – 0.24
Total daily transpiration estimation ($L\ day^{-1}$) / gallons per day ($gal.\ day^{-1}$)	1,750 / 462	1,872 / 494

[a] Sapflow was generally significantly greater in individual caliper trees versus whips for all months except October.
[b] When expressed on a per unit basal area basis ($kg\ cm^{-2}\ hr^{-1}$) rates were generally greater in whips versus caliper trees.
[c] Mean ranges for whips are from June to October; mean ranges for caliper trees are from July to October.

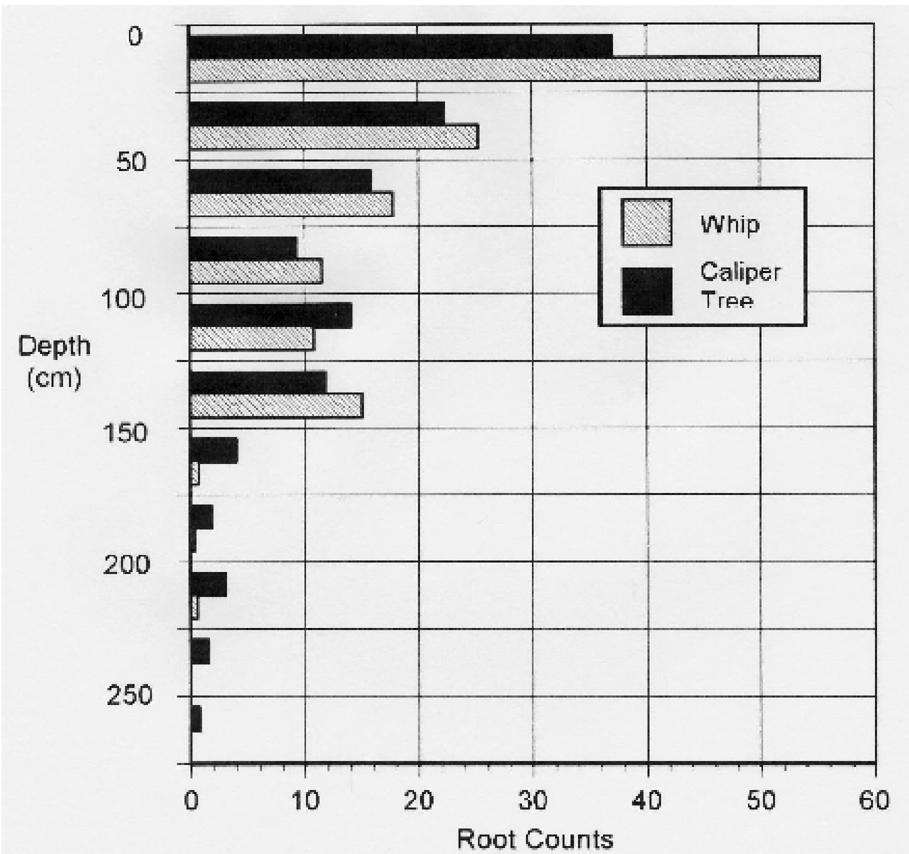


Figure 5. Root Counts by Depth.

Sapflow rate for a mature cottonwood tree (adjacent to the plantations) was measured at 230 kg day-1 (~60 gal. day^{-1}). This rate represents an upper limit of potential transpiration by a single tree at the demonstration site but is nonattainable in a plantation configuration (i.e., canopy closure in both plantations will eventually limit leaf area and limit maximum potential transpiration of individual trees). Therefore, tree spacing at the site will affect the amount of water transpired by individual trees but should not affect the amount of water that will be transpired by the overall plantations as long as canopy closure is eventually achieved (Vose and Swank, 1998).

The planted trees were not expected to reach their transpiration potential during the demonstration; therefore, site-specific climate, sapflow, soil-moisture, and tree-root data were used to parameterize and validate the physiologically based model PROSPER (Goldstein et al, 1974), which was then used to predict evapotranspiration rates likely to occur for closed canopy conditions (maximum transpiration). Depending on model assumptions, the predicted stand-level evapotranspiration for whips and caliper trees during the closed canopy period (year 12 and beyond) was the same and ranged from 25 to 48 cm per growing season (USEPA, 2003).

4.1.4 Hydrologic Effects of Tree Transpiration

The PROSPER model was also used to predict the magnitude and extent of the drawdown cone that may be expected due to future transpiration at the study area. A volumetric groundwater budget was computed for each predictive simulation. Since the model predictions simulate a range of possible climatic conditions, soil-water availability, and root growth for each scenario, there is a range of predicted drawdown and predicted reductions in the outflow of groundwater from the planted area. Predicted drawdown during peak growing season after the trees have achieved a closed canopy (year 12 and beyond) ranges from 12 to 25 cm at the center of the drawdown cone. The diameter of the predicted drawdown cone ranges from approximately 140 m to more than 210 m (Figures 6 and 7).

4.1.5 Contaminant Uptake into Plant Organs

Leaf, stem, and root ("plant tissue") samples were collected from 5 whips, 5 caliper trees, and a proximal mature cottonwood tree on five occasions between October 1996 and October 1998. Analyses of plant tissues were to determine the presence of VOCs, changes in VOC concentrations over time, and difference in VOC concentration between the plantation trees and the mature cottonwood tree. Although thirty VOCs were scanned as part of the method, only seven VOCs were detected in the tissue samples. These detected compounds include TCE, *cis*-1,2-dichloroethene (*c*DCE), methylene chloride, perchloroethylene (PCE), chloroform, toluene, and acrolein (Table 7).

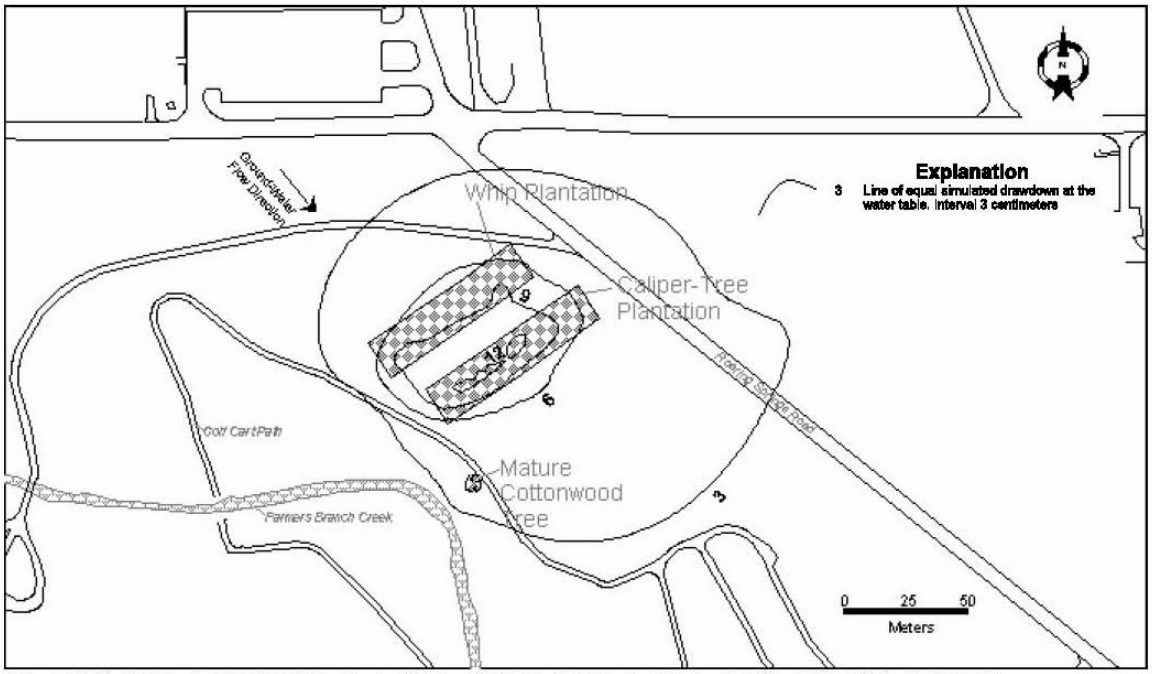


Figure 6. Minimum Predicted Water Table Drawdown for Closed-Canopy Conditions (year 12 and beyond).

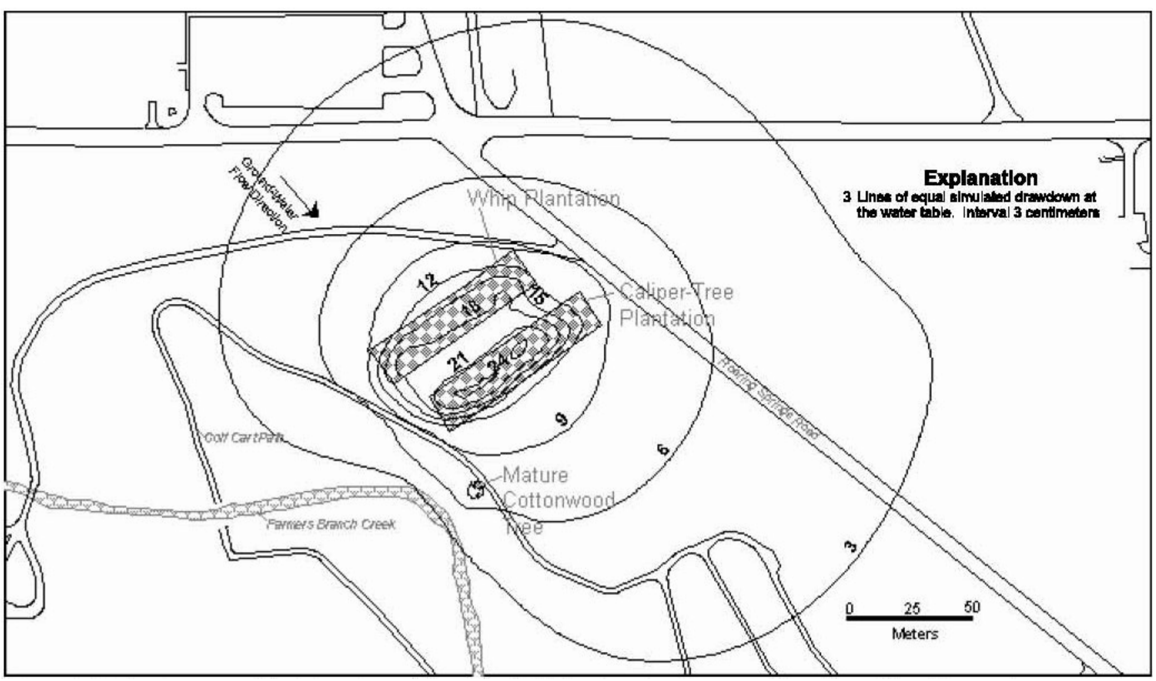


Figure 7. Maximum Predicted Water Table Drawdown for Closed-Canopy Conditions (year 12 and beyond).

Table 7. Average Concentration of Detectable Volatile Compounds in Plant Tissue
(micrograms per kilogram [µg/kg]).

Tree Type	Analyte	Plant Tissue	MEASUREMENT EVENT				
			October 1996	July 1997	October 1997	June 1998	October 1998
Whips	TCE	Leaf	ND	ND	1.6 (2)	ND	ND
		Stem	26 (1)	ND	10.1 (3)	44 (1)	32.8 (5)
		Root	ND	---	---	140	---
	Acrolein	Leaf	ND	58.5 (5)	ND	ND	ND
		Stem	15.2 (3)	136 (3)	20 (1)	ND	14.4 (3)
		Root	21.7 (3)	---	---	25	---
	Chloroform	Leaf	ND	ND	ND	ND	ND
		Stem	3.9 (1)	ND	ND	ND	ND
		Root	ND	---	---	---	ND
	Methylene Chloride	Leaf	ND	151 (5)	8.3 (3)	ND	ND
		Stem	15 (2)	153 (3)	6.6 (2)	ND	ND
		Root	29.3	---	---	---	ND
	*c*DCE	Leaf	ND	ND	ND	ND	ND
		Stem	ND	ND	1.9 (3)	14 (1)	13.5 (5)
		Root	ND	ND	---	ND	---
	Toluene	Leaf	ND	0.73 (2)	ND	1.4 (5)	ND
		Stem	ND	ND	2.3(3)	2.3 (2)	ND
		Root	ND	---	---	1.1	ND
Calipers	TCE	Leaf	ND	ND	10.4 (3)	4.5 (2)	ND
		Stem	ND	ND	9.6 (3)	71 (1)	24.6 (5)
		Root	ND	---	---	13	---
	Acrolein	Leaf	ND	19.1 (1)	ND	ND	ND
		Stem	7.0 (2)	46.2 (5)	12.5 (4)	ND	ND
		Root	9.1 (2)	---	---	ND	---
	Chloroform	Leaf	ND	0.73 (1)	ND	ND	ND
		Stem	4.1 (1)	ND	ND	ND	ND
		Root	ND	---	---	ND	---
	Methylene Chloride	Leaf	ND	168 (5)	ND	ND	ND
		Stem	10 (1)	ND	3.6 (5)	ND	ND
		Root	ND	---	---	ND	---
	*c*DCE	Leaf	ND	ND	ND	ND	ND
		Stem	ND	ND	1.6 (3)	15.7 (3)	8.9 (4)
		Root	ND	---	---	ND	---
	Toluene	Leaf	ND	ND	4.3 (2)	1.1 (2)	ND
		Stem	ND	ND	1.5 (1)	2.0 (1)	ND
		Root	ND	---	---	0.91	---
	PCE	Leaf	ND	ND	ND	ND	ND
		Stem	ND	71 (3)	5.1 (2)	ND	ND
		Root	ND	---	---	ND	---
Mature Cottonwoods	TCE	Leaf	---	ND	ND	ND	ND
		Stem	ND	ND	6.4	13	2.2
	Acrolein	Leaf	---	49	ND	ND	ND
		Stem	ND	35	ND	ND	ND
	Chloroform	Leaf	---	120	ND	ND	ND
		Stem	ND	ND	ND	ND	ND
	Methylene Chloride	Leaf	---	ND	6.3	ND	ND
		Stem	2.2	ND	2.8	ND	ND
	*c*DCE	Leaf	---	ND	ND	ND	ND
		Stem	1.2	ND	10	ND	2.8
	Toluene	Leaf	---	0.7	ND	ND	ND
		Stem	ND	ND	ND	0.9	ND
	PCE	Leaf	---	ND	ND	ND	ND
		Stem	ND	ND	ND	ND	ND

Number in parenthesis represents the number of trees for which analyte detected. Five whips and five caliper trees sampled.
ND = Not detected. Dashed line = Not analyzed for.

The following conclusions can be drawn from the plant tissue VOC data summarized in Table 7:

- Chlorinated compounds were commonly encountered in tissue samples during all five sampling events. The stem samples generally exhibited the greatest diversity and concentration of chlorinated compounds.

- There was a general increase in chlorinated ethenes over time in the percentage of trees containing those compounds (average concentrations also increased). The highest concentrations were encountered during the October 1998 sampling event. All five whip and five caliper tree samples contained detectable levels of TCE in the stems. Average stem concentrations were 32.8 µg/kg for the whips and 24.6 µg/kg for the caliper trees.

- Whip and caliper tree plantations did not significantly differ as to the presence and concentration of VOCs.

- The concentrations of chlorinated ethenes in the plantations was higher than detected in the mature tree.

- An increasing abundance of chlorinated ethenes in the plant tissues over time indicates that the plantations progressively translocated more contaminants from the subsurface over time. These data cannot be used to assess the fate of these contaminants within the plant tissues or to determine if they are volatilized into the atmosphere.

4.1.6 Geochemical Indices of Subsurface Oxidation Reduction

Samples were collected from monitoring locations upgradient of, within, and downgradient of the plantations and from a monitoring point adjacent to the mature cottonwood tree. Specifically monitored were concentrations of TCE, *c*DCE, total organic compound (TOC), CH_4, sulfide, DO, and hydrogen gas; and ferrous and ferric iron ratios. These analyses were used to determine the concentrations and distribution of VOCs and indices of redox conditions within the aquifer and to provide insight into aquifer conditions once the planted trees have matured.

Table 8 summarizes the results of the VOC analyses based on the average concentration within four areas of the site relative to the plantations (i.e., upgradient, plantations, downgradient, mature tree) for each event. The data show a general decrease in TCE concentrations throughout the demonstration site over the course of the study. However, since a decrease in TCE concentration was observed in the upgradient monitoring wells as well as in the wells within the plantations, this trend does not appear to be predominantly related to the establishment of the whip and caliper tree plantations. Secondly, downgradient monitoring wells did not exhibit a significant decrease in TCE concentrations. The change in TCE concentrations within the study area over time may be attributed to dilution from recharge to the aquifer and volatilization of TCE from the water table. The data also indicate that the TCE concentrations in the aquifer beneath the mature cottonwood tree were significantly lower than elsewhere at the demonstration site. In addition, *c*DCE concentrations were much higher beneath the mature tree than upgradient, within, or downgradient of the planted trees (USEPA, 2003).

Table 8. Average TCE, *c*DCE, and *t*DCE Concentrations in Groundwater During Demonstration (micrograms per liter [µg/L]).

Parameter	Location Area of Wells Sampled [1]	SAMPLING EVENT				
		December 1996	May 1997	July 1997	July 1998	September 1998
TCE	Upgradient	818	771	709	480	490
	Plantations	710	548	581	486	420
	Downgradient	512	523	571	478	484
	Mature tree	89	38	31	157	135
*c*DCE	Upgradient	176	174	179	118	158
	Plantations	121	114	157	109	172
	Downgradient	101	109	143	98	145
	Mature tree	160	230	240	150	217
*t*DCE	Upgradient	1.2	3.6	3.6	1.8	7.7
	Plantations	2.4	1.1	3.0	2.3	4.5
	Downgradient	2.0	1.3	3.3	2.0	4.6
	Mature tree	8.8	11.5	12.8	12.5	18.3

[1] Upgradient wells sampled included 501, 502, 503, 513, and 518. Plantation wells included 504, 505, 507, 508, 509, 514, 515, 524, and 525. Downgradient wells included 526, 527, 528, and 529.

4.1.7 Microbial Contributions to Reductive Dechlorination

A reconnaissance study of microbial activity in soil and groundwater beneath the whip and caliper tree plantations, and the proximal mature cottonwood tree, was conducted by the USGS in February and June of 1998. The purpose of the study was to determine 1) the nature of the microbial community at the demonstration site and 2) if the microbial community had evolved into one supportive of reductive dechlorination of TCE and its daughter products. Microbial populations within the area of the tree plantations were found to be similar to the background sites with the exception of locally increased numbers of anaerobic microorganisms and the presence of methanogenic microorganisms. The data collected suggest that the microbial community appeared to be moving towards an assemblage capable of supporting reductive dechlorination by the third growing season (USEPA, 2003).

4.2 PERFORMANCE CRITERIA

There were no specific performance criteria identified for the SRWCGT system operating at the CGC. Specific objectives associated with the 3-year demonstration period (1998-2000) are discussed in Section 3.1, Performance Objectives, and Section 4.0, Performance Assessment. There are, however, regulatory performance criteria for TCE and daughter compounds *c*DCE and VC of 5, 70, and 2 µg/L, respectively (refer back to Table 1).

- There are two performance issues (a.k.a. criteria) identified in Eberts et al, 2005, with regard to the studies conducted after the 3-year demonstration period. As stated, for microbial processes, it is necessary to (1) determine whether the observed changes in groundwater chemistry can take place at rates that are protective of human health and the environment and (2) whether the microbial processes responsible for the changes will continue for an acceptable period of time (National Research Council, 2000 and Azadpour-Keely et al, 2001). These two performance issues are addressed in Section 4.3.2.

4.3 DATA ASSESSMENT

4.3.1 Demonstration Data Assessment

During the 3-year demonstration, both whip and caliper tree plantations began utilizing the aquifer and reduced the volume of contaminated groundwater leaving the site. The maximum reduction in the outflow of contaminated groundwater that could be attributed to the trees was approximately 12% (observed at the peak of the third growing season). At this time, the maximum observed drawdown of the water table (approximately 10 cm) occurred near the center of the treatment system, and the reduction in the mass flux of TCE across the downgradient end of the treatment system was closer to 11% because TCE concentrations were slightly higher during the third growing season than at baseline.

By September of the second growing season (1997), tree roots in both plantations had reached the water table (275 cm for whips; 225 cm for caliper trees). By the end of the third growing season, whips (planted about 1.25 m apart) were starting to approach canopy closure. The caliper trees (planted 2.5 m apart) were not as close to canopy closure. Nonetheless, individual caliper trees transpired just over twice as much water as individual whips (although transpired volume of water by both plantations was similar due to the difference in tree number). A groundwater flow model (MODFLOW) of the study area indicated the volume of water transpired from the aquifer during the peak of the third growing season to be probably closer to 20% of the initial volume of water that flowed through the site due to an increase in groundwater inflow to the site resulting from an increased hydraulic gradient on the upgradient side of the drawdown cone.

During the third growing season, actual reduced volumetric flux of contaminated water out of the site, due to tree transpiration, was evidenced by decreases in hydraulic gradient across the downgradient end of the planted area. In June 1998, the largest reduction in hydraulic gradient occurred and measured at 10%. The saturated thickness of the aquifer at the downgradient end of the site also decreased. The maximum drawdown that could be attributed to the trees during June 1998 was observed between the two plots and was measured at 10 cm). At this stage of system development, a drawdown cone was apparent, but there remained a regional hydraulic gradient across the site that resulted in most of the contaminated groundwater flowing outward across the downgradient end of the planted area.

In summary, the first three growing seasons at the demonstration site resulted in a reduction in the contaminant mass moving off site. The maximum observed reduction in the mass flux of TCE across the downgradient end of the demonstration site was 11%. At demonstration's end, the following conclusions were made:

- An observed general decrease in the concentration of TCE throughout the demonstration site over the course of the study does not appear to be predominantly related to establishing whip and caliper tree plantations because (1) decreased TCE concentrations were observed both in upgradient wells and in wells within the plantations; (2) wells downgradient of the plantations did not exhibit a significant decrease in TCE concentration, and (3) TCE concentrations beneath the mature cottonwood tree were significantly lower than at other site locations.

- Although significant reductive dechlorination of VOCs had not occurred across the demonstration site by demonstration's end, there is evidence that the aquifer beneath the planted trees was beginning to support anaerobic microbial communities capable of biodegradation of TCE within three years of planting (i.e., microbial data from soil and groundwater samples indicated the microbial community beneath the planted trees had begun to move towards an assemblage capable of supporting reductive dechlorination).

- The ratio of TCE to *c*DCE had also decreased beneath the whip plantation where the water level was closest to land surface, suggesting that the shift toward anaerobic conditions in this part of the aquifer was beginning to support the biodegradation of TCE (Significant contaminant reduction by this mechanism, however, had not occurred across the demonstration site by the end of the demonstration period).

- Data from the aquifer beneath the mature cottonwood tree near the plantations showed (1) a TCE/*c*DCE ratio beneath the mature tree typically one order of magnitude less than elsewhere at the site during the demonstration and (2) microbial populations in this area consisting of a vigorous community supporting both hydrogen oxidizing and acetate fermenting methanogens (assumed responsible for decreasing TCE and generating daughter products, such as VC, beneath the mature cottonwood tree). These findings indicate that reductive dechlorination can occur beneath cottonwood trees with established root systems.

- Based on plant tissue data, it was concluded that the planted cottonwood trees have properties that are effective in degrading TCE. An investigation into the kinetics of transformation of TCE for leaf samples concluded that degradation within the trees is not likely to be the rate-limiting step in a SRWCGT system (USEPA, 2003).

- The data collected during the demonstration are insufficient to conclude when significant reductive dechlorination will occur beneath the planted trees; the change in TCE concentration within the study area over time may be attributed to dilution from recharge to the aquifer and volatilization of TCE from the water table.

- There is no field evidence from the demonstration study to suggest that complete in situ biodegradation of TCE and its daughter products can be achieved.

4.3.2 Follow-On Study Results

The data collected during the demonstration (i.e., up through the end of the third growing season) was insufficient to conclude when significant reductive dechlorination will occur beneath the planted trees (USEPA, 2003). As a result, evaluation at the CGC continued after the third growing season (post-demonstration). Post-demonstration data assessment has been an ongoing effort. Groundwater chemistry has been investigated as recently as January 2005 (Harvey, 2005); however, the continued data collection and analyses are beyond the scope of this report. The follow-on studies conducted either to directly support or enhance the information collected during the 3-year demonstration, or conducted as supplemental research are summarized in the following discussions.

Evaluation of Long-Term Geochemical Changes in Groundwater (Eberts et al, 2005) and the Effects of Water-Level Variations on Tree Growth and Mortality (Braun et al, 2004).

The Eberts et al (2005) study was essentially a continuation of the demonstration, but emphasized the relation of biodegradation rates to the age of tree plantations. Data was collected up through 2001 and included field analysis of VOCs in groundwater for acquiring TCE/*c*DCE ratios and measurement of parameters that would be indicators of changes in redox due to increased DOC at the site. The study also used a model to compare baseline (1996) and sixth growing season (2001) first order biodegradation rates for TCE, *c*DCE, and VC (see Section 4.3.3 for details).

Data collected during the fifth dormant season (2000) indicated that the aquifer was generally anaerobic beneath the planted trees while it was aerobic upgradient and downgradient of the trees. By near study's end (July 2001), many of the water quality parameters measured continued to support this observation. The TCE/*c*DCE ratios, as calculated from field analyzed concentrations (i.e., via a Photovac 10S50 GC) of TCE and *c*DCE, generally decreased beneath and downgradient of the plantations, but the decreases were sporadic. Table 9 summarizes mean concentrations of several of the redox-indicating parameters relative to plantation location.

Mean TCE concentrations decreased site-wide from 532 µg/L in July 1997 to 182 µg/L in July 2001. However, decreases in TCE concentrations with time were also observed upgradient of the site. This general decrease in TCE concentrations throughout the entire plume may have resulted from reductions in source material or natural attenuation processes (e.g., dilution from recharge and volatilization between the contaminant source and the site). Vertical patterns in TCE concentrations across the saturated thickness of the aquifer were not observed at the site.

Table 9. Mean Concentrations of Water Quality Parameters as of July 2001 (µg/L) (Eberts et al, 2005).

Parameter	LOCATION RELATIVE TO PLANTATIONS: Immediately Upgradient	Directly Beneath	Downgradient (up to 40 feet)	Beneath Mature Cottonwood
TCE/*c*DCE ratio [1]	Generally remained above 4 during the study	Generally decreased over time, except between Jan - July 2001	generally decreased over time, except for July 2001	remained fairly stable (<2)
DO (mg/L)	3.06	1.69	1.01	0.69
Nitrate (mg/L)	3.23	2.10	1.22	0.66
Ferrous Iron (mg/L)	0.05	0.08	0.7	0.5
Sulfide (mg/L) [2]	See footnote 2			
Methane (mg/L) [3]	See footnote 3			
Alkalinity (mg/L) [4]	322	377	386	378

[1] TCE/cDCE ratios were calculated from TCE and *c*DCE concentrations measured in the field via a Photovac 10S50 GC.
[2] Sulfide concentrations were below detection or very low across most of site during study period. Notable exceptions were wells 514, 515, 527 and 528, where sulfide first appeared in January 2000. Since then, concentrations have ranged from 0.01 to 0.55 mg/L. No site-wide temporal trend has been observed.
[3] Methane has consistently been detected in well 511 beneath the mature cottonwood tree. It also has been detected in wells 514, 516, and 517 in the whip plantation since July 2000. In addition, methane has been detected in well 515 in the sapling plantation and in wells 527 and 528 immediately downgradient of the plantations. Concentrations in these wells ranged from 0.005 to 0.9 mg/L in July 2001.
[4] Alkalinity was measured as bicarbonate.

Due to the general decrease in TCE concentrations with time, changes in the TCE/*c*DCE ratio were used to identify changes in groundwater chemistry that can be attributed to the trees. Most TCE/*c*DCE ratios for groundwater from the site were 4 or larger in 1997. Mean upgradient ratios generally remained above 4 during the period of study. The mean ratios for ground water from wells within the plantations generally decreased over time, except between January 2001 and July 2001 (mean ratio increased from 2.7 to 4.5); mean downgradient ratios also decreased over time except for July 2001. Ratios for wells beneath the mature tree remained fairly stable (< 2) during the study.

VC was detected in six wells by July 2001; concentrations ranged from 1.4 to 28 µg/L. Concentrations of VC in wells beneath the mature tree were as high as 16 µg/L at the time. Because the aquifer that surrounds the plantations is consistently aerobic and aerobic oxidation of VC can be significant (Chapelle 2001), generation of VC is not an issue of concern for this site (Eberts et al, 2005).

According to Eberts et al (2005), this follow-on study resulted in the following basic conclusions:

- The planted trees can serve as a sustainable source of electron donors, supplying DOC to the underlying aquifer over the long term and thereby supporting in situ processes related to TCE degradation. Trees planted in areas where the depth to groundwater was less than 3 m (9.8 ft) were able to deliver enough DOC to the aquifer to:

  - Lower DO concentrations
  - Create iron-reducing conditions along the plume centerline
  - Create sulfate-reducing or methanogenic conditions in localized areas
  - Initiate in situ reductive dechlorination of TCE.

- The combined results suggest that, after 6 years, in situ biodegradation was becoming the dominant process contributing to the reduction in the mass flux of TCE across the site, whereas transpiration directly from the aquifer was the dominant process during the first 3 years after planting.

- From the time the plantations were approximately 5 to 6 years old, microbial activity appears to have been enhanced year round (i.e., including notable activity during the dormant season).

- The presence of TCE daughter products and residual TCE indicates that the reductive dechlorination process has not fully mineralized the contaminants of concern to innocuous compounds. Consequently, just a few rows of trees may not be enough to provide sufficient organic carbon to significantly influence the natural attenuation capacity of a large, highly oxic, and transmissive aquifer.

Although Eberts et al (2005) focused on VOC in wells along the centerline of the plume, VOC monitoring for the entire set of wells monitored during the demonstration was continued through the sixth growing season (2002). The results for TCE and *c*DCE (Table 10 and Table 11,

respectively) are included in Braun et al (2004), a report that investigated biogeochemical parameters and water-level variations at the demonstration site and discusses how the water-level variations affected tree growth and mortality.

Table 10. Post-Demonstration TCE Concentrations Through July 2002
(µg/L) (Braun et al, 2004)[1].

Well ID	SAMPLING EVENT					
	June 1998 *	**Sept. 2000**	**Jan. 2001**	**July 2001**	**Jan.-Feb. 2002**	**July 2002**
Wells Upgradient of Plantations						
WJEGTA 501	460	---	180	200	170	160
WJEGTA 502	510	160	200	240	140	170
WJEGTA 503	530	---	200	180	150	180
WJEGTA 513	---	---	230	230	150	180
WJEGTA 518	420	200	150	220	190	170
Average	480	180	190	210	160	170
Wells Within/Between Plantations						
WJEGTA 504	560	---	150	180	140	130
WJEGTA 505	490	---	160	200	170	120
WJEGTA 507	440	---	150	210	190	150
WJEGTA 508	450	---	130	190	160	180
WJEGTA 509	500	---	110	180	150	150
WJEGTA 514	420	120	72	110	130	150
WJEGTA 515	390	60	34	160	51	130
WJEGTA 516	540	240	160	270	230	170
WJEGTA 517	470	---	190	250	190	Q200
WJEGTA 519	600	190	180	230	140	130
WJEGTA 520	450	---	150	200	170	190
WJEGTA 521	580	---	180	240	170	180
WJEGTA 522	---	---	200	210	190	180
WJEGTA 523	500	---	170	190	190	160
WJEGTA 524	600	220	180	230	180	180
WJEGTA 525	460	---	140	210	130	150
Average	500	170	150	200	160	160
Wells Downgradient of Plantations						
WJEGTA 526	490	240	150	220	180	160
WJEGTA 527	540	---	40	110	12	Q51
WJEGTA 528	380	---	24	75	1.2	47
WJEGTA 529	500	---	150	220	170	160
Average	480	240	91	160	91	100

[1] Values reported to two sig. digits. Q = elevated reporting limit. * June 1998 samples field-analyzed (Photovac GC); other samples lab analyzed.

Evaluation of Uptake of Groundwater Versus Surface Water by the Eastern Cottonwood Trees (Clinton et al, 2004)

This July 2000 study examined the relative uptake of surface water versus groundwater by mature trees for determining the relative contribution of groundwater to plant transpirational water use. Three types of measurements were used to meet the objective: isotope measurements in irrigation versus groundwater and in tree sap; sapflow measurements used to estimate tree transpiration rates; and TCE concentrations in xylem sap.

Table 11. Post-Demonstration cTCE Concentrations Through July 2002
(µg/L) (Braun et al, 2004)[1].

Well ID	SAMPLING EVENT					
	June 1998	Sept. 2000	Jan. 2001	July 2001	Jan.-Feb. 2002	July 2002
Wells Upgradient of Plantations						
WJEGTA 501	110	---	31	37	30	26
WJEGTA 502	130	33	34	40	27	28
WJEGTA 503	130	---	34	33	30	29
WJEGTA 513	---	---	39	43	33	30
WJEGTA 518	100	39	29	39	30	26
Average	120	36	33	38	30	28
Wells Within/Between Plantations						
WJEGTA 504	120	---	50	39	45	26
WJEGTA 505	110	---	39	38	35	21
WJEGTA 507	91	---	69	45	36	28
WJEGTA 508	95	---	83	40	33	33
WJEGTA 509	100	---	71	40	33	30
WJEGTA 514	150	47	72	82	51	47
WJEGTA 515	92	24	31	45	25	32
WJEGTA 516	120	47	52	46	42	30
WJEGTA 517	110	---	39	46	44	30
WJEGTA 519	140	53	53	68	37	45
WJEGTA 520	92	---	55	41	32	31
WJEGTA 521	120	---	41	44	30	29
WJEGTA 522	---	---	37	38	33	30
WJEGTA 523	100	---	45	36	38	28
WJEGTA 524	130	48	44	44	37	35
WJEGTA 525	95	---	42	49	32	33
Average	110	44	51	46	36	32
Wells Downgradient of Plantations						
WJEGTA 526	99	47	50	45	40	33
WJEGTA 527	120	---	100	48	41	16
WJEGTA 528	75	---	34	42	1.9	15
WJEGTA 529	97	---	58	46	44	33
Average	98	47	61	45	32	24

[1] Values reported to two sig. digits. Q = elevated reporting limit. * June 1998 samples field-analyzed (Photovac GC); other samples lab analyzed.

Irrigation water was used to simulate precipitation (i.e., surface water). To distinguish irrigation water from groundwater, stable isotopes of hydrogen (D) and oxygen (^{18}O) were measured to determine isotopic ratios. (All water sources had distinctly different isotopic ratios; the irrigation water was substantially more enriched in both ^{18}O and D relative to groundwater.) Irrigation water was applied via drip hoses around two mature Eastern cottonwood trees on two consecutive mornings at a rate of 1,600 L/hr (equivalent to 5 cm of rainfall). Based on groundwater elevations and hydraulic conductivity values, the irrigation water did not reach the water table during the course of the study. Volumetric soil water content increased 86% following the first irrigation, decreased 6% between irrigation events, and increased 13% after the second irrigation. Sapflux rates before and after irrigation were compared.

Sapflow was measured continuously over a 4-day period via 5 sapflow probes installed at 5 levels up the stem of each of the two trees. Sapflow velocity (cm h^{-1}) was converted to sapflux (cm3 h^{-1}) based on the cross-sectional area of sapwood at each level and then converted to a

mass basis (kg h^{-1}). Sapflux rates increased by 11% following the first irrigation to 61% after the second irrigation and remained elevated the day following the second irrigation.

TCE was measured in tree core xylem sap within 12 tree cores before and after irrigation. There was an observed decrease in average xylem sap TCE concentration following irrigation (an average of 977 ppb before versus an average of 767 ppb after). To the researchers, the dilution of TCE in tree xylum sap indicated uptake of nonpolluted irrigation water. Because the magnitude of the dilution was disproportionately small relative to a maximum 61% sapflux increase, the researchers also concluded that, although the primary source of TCE was groundwater, the contaminant may have also been present in soil water. Hydraulic lift was speculated as a possible mechanism for transferring TCE to surface soil horizons, which could have possibly resulted in the observed increase in total TCE flux in xylem sap following irrigation. (TCE concentration in soil water was not measured as part of the study.)

The overall conclusion of the study was that water use by the Eastern cottonwood tree is variable depending on water availability and transpirational demand. Although this is an advantage in sustaining the tree, studies addressing phytoremediation effectiveness must account for the relative proportion of surface versus groundwater uptake (i.e., if trees switch to surface water sources when soil water supply is adequate, the overall effectiveness of the phytoremediation treatment will decrease because less pollutant is extracted from the groundwater).

Evaluation of Uptake of Groundwater Contaminants into Tree Trunks of Various Species (Vroblesky et al, 2004)

This study examined tree cores of 100 trees between 1998 and 2002 at three separate sites, including the CGC site. The purpose of the study was to determine if sampling and analysis of tree cores was an effective technique for delineating groundwater contamination by chlorinated ethenes. According to Harvey (2005), tree coring is a technique that is potentially a rapid and inexpensive reconnaissance tool for directing the placement of shallow wells and delineating a shallow plume in two dimensions.

At the CGC site, 29 trees and 10 species were cored between 1998 and 2000, including 12 Eastern cottonwoods, 6 oaks, 3 cedars, 2 willows, 1 hackberry, 1 pecan, 1 pine, 1 American elm, 1 unidentified elm, and 1 unidentified species. Cores were collected from a height of approximately 1.5 m above ground surface. Stem cuttings were also collected from selected Eastern cottonwood trees and analyzed for TCE. The TCE concentrations from these stem cuttings were compared to TCE concentrations in tree cores collected from the same tree.

Data from the CGC site show that the presence of TCE and *c*DCE in tree cores can be indicators of subsurface contamination. The data also imply that within an individual tree species, higher groundwater TCE concentrations can produce higher tree core TCE concentrations. Regarding the comparison of tree cores to same-tree stem cuttings (for samples collected in 2001-2002), TCE concentrations found in tree cores were in almost all cases higher than concentrations found in the small stems branching from the trunk (Vroblesky et al, 2004).

4.3.3 Predicted Future Performance and Other Observations

There are two aspects of the SRWCGT system that were predicted by modeling: hydraulic control of contaminated groundwater and reductive dechlorination of TCE and other contaminants. Each of these performance aspects is summarized in this section. The models used to predict performance of the SRWCGT system at CGC included:

- PROSPER (Goldstein et al, 1974)—A mechanistic model of sapflow used to estimate stand-level transpiration for the phytoremediation system once the canopy closes

- MODFLOW (McDonald and Harbaugh, 1988)—A groundwater flow model used to predict observed effects of tree transpiration on the aquifer

- BIOCHLOR (Aziz et al, 2000)—An analytical solute transport model used to estimate first-order biodegradation rates for the chlorinated organic compounds detected at the site.

Hydraulic Control

When the tree plantations achieve a closed canopy, the groundwater flow model MODFLOW predicts the likely reduction in the volumetric flux of contaminated groundwater across the downgradient end of the site to be between 20% and 30% of the initial amount of water that flowed through the site. The actual amount of water that will be transpired from the aquifer by the tree plantations will be closer to 50% to 90% of the volume of water that initially flowed through the site. The discrepancy between the reduction in the volumetric outflow of groundwater and the volume of water transpired from the aquifer can be attributed to the predicted increase in groundwater inflow to the site and the release of aquifer-stored water (USEPA, 2003).

The physiologically-based model PROSPER predicted that the whip and caliper tree plantations will eventually transpire a similar amount of water (25 to 48 cm per growing season), depending on climatic conditions, soil moisture, and root growth. The contaminated aquifer (saturated zone) is expected to supply 48% to 58% of this predicted evapotranspiration, regardless of the planting strategy. No hydraulic control is predicted for future dormant seasons (November through March) at the CGC site (USEPA, 2003).

Biodegradation Rates

In July 2001 systematic flowpath changes in groundwater chemistry were observed along the TCE plume centerline at the demonstration site, which allowed for estimating changes in first order biodegradation rate constants of chlorinated compounds that were attributable to the trees. Simulation of processes along the plume centerline allows for conservative estimates of the potential performance of the phytoremediation system because groundwater and contaminant velocities are likely to be greatest along the plume centerline, and biodegradation rates must be highest where velocities are greatest in order to achieve cleanup goals (Eberts et al, 2005). First order biodegradation rate constants for TCE and daughter products *c*DCE and VC were

estimated for baseline (1996) and for the sixth growing season (2001), using the analytical solute transport model BIOCHLOR (Aziz et al, 2000). Table 12 presents the input parameters for the model.

Table 12. Input Parameters for BIOCHLOR Analytical Solute Transport Model.

BIOCHLOR Model Input Parameters	Baseline (December 1996)	Sixth Growing Season (July 2001)
Groundwater velocity	0.5 m/day	0.8 m/day
Longitudinal dispersivity [1]	3m	3m
Transverse to longitudinal dispersivity ratio	0.1	0.1
Vertical dispersivity [2]	See footnote 2	See footnote 2
Soil bulk density [3]	1.6 kg/L	
Fraction organic carbon value [4]	0.0016	0.0016
Organic carbon partition coefficients for the various solvents [5]	See footnote 5	See footnote 5
Simulation time	1 year	1 year
Source thickness (saturated thickness of the aquifer at well 521)	1.4 m	1.3 m

[1] The estimated value is near the low end of the range for plumes at a similar scale (Gelhar et al, 1992).
[2] An extremely low value was selected to approximate no vertical dispersivity.
[3] The average soil bulk density for sand presented by Wiedemeier et al, 1998.
[4] Determined from site-specific soil samples
[5] Acquired from Wiedemeier et al, 1998

Table 13 provides a comparison of values for selected parameters as determined in 1996 to those same values as determined in 2001. The BIOCHLOR-simulated estimates for July 2001 first-order biodegradation rate constants for sequential reductive dechlorination of TCE, *c*DCE, and VC are 0.02/day, 0.04/day, and 0.82/day, respectively. These values represent a notable increase in biodegradation rates compared to rates simulated for the same flowpath at baseline conditions. The July 2001 rate constant for VC is high compared to the average field rate of 0.002/day for dechlorination of VC in Aronson and Howard (1997). The high-modeled rate of VC degradation by means of reductive dechlorination for the flowpath suggests that another degradation pathway may be present; for example, *c*DCE and VC can degrade by means of oxidation in iron-reducing conditions (Chapelle, 2001). The absence of VC accumulation along the flowpath is possibly due to such oxidative pathways. The July 2001 biodegradation rate for TCE is associated with a half-life of 36 days. A half-life of 2 days was determined for TCE in laboratory microcosms of soil from the site and represents the degradation potential of the microbes in the aquifer beneath the plantations (E.M. Godsy, 2000).

Table 13. Comparison of Estimated Biodegradation Indices for Site Aquifer—1996 Versus 2001.

Parameter	EVENT	
	Baseline (1996)	Sixth Season (July 2001)
Estimated biodegradation rate constants (day^{-1}) [a]		
TCE	0.0002	0.02
*c*DCE	0.0001	0.04
VC	0.0005	0.82
Natural attenuation capacity (m^{-1}) [b]	0.0004	0.024
Plume stabilization distance for TCE (m) [c]	9,680	160

[a] First-order biodegradation rates along centerline of the plume; calculated using BIOCHLOR (Aziz et al, 2000).
[b] Natural attenuation capacity (NAC) refers to the quantity $[-v+(v^2+4Dk)^{1/2}]/2D$ where v is the groundwater velocity, D is the coefficient of hydrodynamic dispersion, and k is the biodegradation rate constant.
[c] Distance in which TCE concentrations could be expected to degrade to the MCL of 5 µg/L, given an NAC value of 0.024/m.

The only conclusive information on the future timing of significant reductive dechlorination in the aquifer, however, can be extrapolated from the mature tree. The mature cottonwood was approximately 20 years old during the demonstration; as a result, the planted site will likely reach this level of contaminant reduction within this time frame (USEPA, 2003).

4.4 TECHNOLOGY COMPARISON

The SRWCGT system at the CGC site is being implemented as both a source control and a type of biological treatment system. Therefore, it is difficult to place such a system into a single classification for comparison with other treatment technologies. A SRWCGT system may best be compared to other treatment systems conducive to treating chlorinated organics (such as TCE) in groundwater. These may include, but are not limited to, natural attenuation (dilution dispersion, sorption, volatilization), in situ biodegradation, and conventional pump and treat (ex situ).

Natural Attenuation

Both fuels and chlorinated solvents (such as TCE) can naturally attenuate if the appropriate conditions exist in the subsurface. Natural attenuation in groundwater systems results from the integration of several subsurface mechanisms classified as either destructive or nondestructive. Biodegradation is the most important destructive mechanism. Nondestructive mechanisms include sorption, dispersion, dilution from recharge, and volatilization. The biodegradation of fuel products is limited by electron acceptor availability (Wiedemeier et al, 1996).

Fortunately there is an adequate supply of electron acceptors in most hydrologic settings so most fuels plumes degrade faster than they move (Chapelle, 2000). The long-term behavior of chlorinated solvents is more difficult to predict than fuel plumes. The biodegradation of chlorinated solvents begins in the saturated subsurface where native or anthropogenic carbon is used as an election donor, and DO is utilized first for the prime electron acceptor (Wiedemeier et al, 1996). Once DO is depleted, anaerobic microorganisms most often use available electron acceptors in the following order: nitrate, Fe(III) hydroxide, sulfate, and CO_2 (Chapelle, 2000). In the absence of nitrate and DO, chlorinated solvents compete with other electron acceptors and donors, especially sulfate and CO_2. The most important anaerobic process for the natural biodegradation of chlorinated solvents is reductive dechlorination. When a chlorinated solvent is used as an electron acceptor, a chlorine atom is removed and replaced with a hydrogen atom. Electron donors include fuel hydrocarbons, landfill leachate or natural organic carbon. If the subsurface is depleted of electron donors before chlorinated solvents are removed, microbial reductive dechlorination will cease (Wiedemeier, 1996). Plumes of chlorinated solvents can naturally attenuate, but they do not almost 80% of the time due to the lack of electron donors (Chapelle, 2000).

In Situ Bioremediation

In situ bioremediation can be generally used to describe any bioremediation technology that involves using either proprietary bacteria strains or indigenous microorganisms to degrade contaminants in situ. Typically, the technology involves injecting microbial formulations and/or bacterial enhancements (i.e., chemicals or other amendments) into the groundwater via wells to

initiate or enhance bioremediation. In situ reactive barriers, which usually have a bioremediation component, would also fit under the general category of in situ bioremediation.

Because one of the processes associated with tree-based phytoremediation systems is phytostimulation (i.e., plant roots excreting compounds containing organic carbon that is used as a food source for microorganisms), there can be a direct comparison to in situ bioremediation. The main differences are that conventional in situ bioremediation systems typically become effective upon injecting the bacteria and/or enhancements (and thus treat contaminants more quickly) and are not restrained by depth. An example of such a technology, used for treating the same compounds detected at the CGC, is an enhanced in situ bioremediation technology developed by the Department of Energy (DOE). The PHOSter™ process was evaluated during a field demonstration conducted between March 1998 and August 1999 at a manufacturing facility to determine its effectiveness in treating a fractured bedrock aquifer contaminated with TCE, cDCE, and other chlorinated VOCs. This particular process involved injection of air, methane (carbon source), nitrous oxide (nitrogen source), and triethyl phosphate (phosphorus source) into an aquifer to enhance biodegradation. Results showed that there were significant reductions in target VOCs in monitoring wells designated critical to the study, with higher than expected removals observed in an upper zone of the aquifer relative to the lower zone (Gallardo et al, 2002). A tree-based phytoremediation system would not have been appropriate at this site because the tree roots could not have penetrated the shallow bedrock aquifer deep enough to reach the contamination.

Conventional Pump and Treat

Pump and treat, an ex situ technology, is sometimes used as a metaphor for tree-based phytoremediation systems. The ability of trees to act as pumps was noted in the late 19th century when eucalyptus trees were planted in Italy and Algeria to dry up marshes (USEPA, 2003). Specifically for the demonstration, it was hypothesized that tree physiological processes would result in the reduction of TCE mass flux in the aquifer due to a combination of hydraulic control of the contaminant plume and in situ reduction of the contaminant mass (natural pump and treat). There was a 12-extraction well pump and treat system distributed over an approximate 5-acre area of the CGC prior to the installing the SRWCGT system (Walters, 2004). This system was installed to help remediate a finger of the large TCE plume.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

The following section presents an estimation of the costs for the demonstration and associated studies regarding the SRWCGT system installed at the CGC, estimated real-world costs when implemented at a scale similar to the demonstration, and scaled-up costs for a hypothetical full-scale site.

5.1.1 Actual Demonstration Costs

There were three funding entities associated with the CGC demonstration and associated studies. These included DoD's Environmental Security Technology Certification Program (ESTCP), which provided initial startup funding of the project; the USEPA SITE Program, which provided much of the field monitoring and sampling, and analytical costs during the 3-year demonstration; and the DoD Aeronautical Systems Center/Engineering Directorate (ASC/ENV) of the U.S. Air Force (USAF), which funded other entities such as the U.S. Geological Survey (USGS) and U.S. Department of Agriculture's (USDA) Forest Service (FS). It should also be noted that the majority of costs with the CGC demonstration were for extensive technical support, reports, analytical program, posters, papers, and presentations to validate various changes in the geochemistry, tree water usage, and groundwater hydrology. Many of the actual costs have not been made available for inclusion in this report. However, some actual labor costs for the SITE Program contractor are presented in Table 14.

Table 14. Estimated Demonstration Costs.

Category	Description	Cost
SITE PROGRAM - ACTUAL LABOR COSTS [1]		
Test plan	Evaluating the Demonstration Plan and preparing an addendum to the plan	$86,476
Sampling	Sampling of soil, groundwater, and tree tissue (6 events; Aug. '96 – Oct. '98)	$303,973
Data analysis	Evaluating dehalogenase data from an SAIC contracted laboratory	$5,265
Report preparation	Preparation of several sections of an Innovative Technology Evaluation Report (ITER) (EPA Report)	$8,864
QA-related costs	Investigation/documentation regarding an Air Force laboratory audit and review of dehalogenase raw data	$21,849
Subtotal		**$426,427**
SITE PROGRAM - OTHER DIRECT COSTS [1]		
Specialized Laboratories	VOC and haloacetic acids analyses of plant tissue, ions, TOC, metals, pH analyses, and method development	$70,816
Miscellaneous costs	Geoprobe®/other professional services, materials/supplies, rental, and shipping	$53,299
Travel expenses	Travel, lodging, and per diem	$48,625
Subtotal		**$172,740**
SITE PROGRAM – ESTIMATED EPA LABORATORY COSTS [2]		
Groundwater analyses	Based on 198 samples over six events @ $150/sample	$29,700
Soil analyses	Based on 84 samples over six events @ $150/sample	$12,600
Subtotal		$42,300

Table 14. Estimated Demonstration Costs. (continued)

Category	Description	Cost
Total Estimated SITE Program Demonstration Costs		**$641,467**
DoD – FUNDED COSTS (actual and estimated) [3]		
Costs thru 2-01-96	Demo. Plan prep., solicit bids, confirmation sampling, project management	$109,700
USAF Estimate	Mature tree study, well installation/oversight, USGS support, tree irrigation	$217,000
UGA Estimate	Labor, supplies, travel expenses, etc. associated with "Root Growth Study"	$54,784
FS Estimate	Two-year transpiration study conducted by FS Coweeta Hydrologic Lab.	$197,466
NERL Estimate	Dehalogenase screening study conducted by NERL Athens	$45,000
Total Estimated DoD-Funded Demonstration Costs		**$623,950**
TOTAL ESTIMATED DEMONSTRATION COSTS (through 2003)		$1,265,417

[1] Based on SAIC cost records
[2] Based on estimated of number of samples shipped to EPA and estimate of laboratory costs for those analyses
[3] Based on actual cost and proposals within Technology Demonstration Plan (Jacobs Engineering Group. August 1996)

5.1.2 Estimated Implementation Costs at Field Scale

The SRWCGT system installed at the CGC was field scale, consisting of two rectangular tree plantations, each about 12,000 ft^2 (~ ¼ acre). However, the area of aquifer affected, based on predicted water table drawdown (year 12 and beyond) ranged from approximately 140 m to more than 210 m (USEPA, 2003). This corresponds to 211,000 ft^2 (4.84 acres) to 640,000 ft^2 (14.7 acres). The scope of the research-oriented demonstration involved substantial testing and monitoring of the SRWCGT system that was well beyond typical requirements for site remediation. Real-world costs when implementing a similar SRWCGT system at a scale similar to the demonstration should only include costs essential for achieving cleanup requirements. Table 15 presents the demonstration cost items deemed essential for a typical SRWCGT system remediation project and cost items considered strictly research-oriented and thus unnecessary for such a remediation project.

Table 15. Essential Versus Nonessential Costs for an SRWCGT System[1].

Essential Costs	Nonessential Costs [2]
Purchase of trees	Above-ground biomass measurements
Tree installation	Transpiration measurements of trees
Drip Irrigation system [3]	Tree root growth, distribution, and biomass estimation
Maintenance of tree plantations [4]	Tree trunk sampling for chloroethenes
Monitoring well installation	Water-use habits of trees (surface water versus groundwater)
Long-term groundwater monitoring [5]	Microbial population enumerations in soil and groundwater
	Contaminant uptake into plant tissue

[1]Assumes the site has been fully characterized to a point where phytoremediation has been selected over alternatives, such as natural attenuation
[2] Costs for these research-oriented tasks were incurred for the demonstration but are deemed nonessential for typical remediation projects
[3] Essential for the CGC. Plantations would have failed in summer of 1996, one of the driest recorded summers in Texas (USEPA, 2003)
[4] Maintenance activities such as weed control are imperative during the establishment phase of an SRWC (USEPA, 2003)
[5] Includes periodic water level measurements and groundwater sampling

Due to the relative low expense of tree cuttings needed to establish plantations, the quantity ordered should exceed that anticipated for planting. Some vendors offer cuttings in various lengths ranging from 8 to 36 inches or more. It is often possible to get volume discounts by ordering large quantities. Typically, the longer the cutting the more expensive it is. Spring 2000 prices for 8-9 inch hybrid poplar cuttings were approximately $ 0.25 each for quantities of 25 to 100 to approximately $0.16 for orders of 5,000 cuttings or more. Spring 2000 prices for 18-inch cuttings were about $0.30 and 36-inch cuttings were about $0.50. Shipping and handling charges are usually extra (USEPA, 2003).

Labor-intensive tree installation and tree maintenance costs can be highly variable. It is possible to plant cuttings by hand or by machine. Usually, small scale sites of a few acres are planted by hand, and larger sites are planted by machine. Hand planting rates are reported by Hansen to be 3 acres per day per person and machine planting rates are 20 acres per day per 3-person crew. Once planted, proper soil moisture and weed control are critical for a successful first year. Weeds can be controlled by cultivation, mulching, and herbicides (USEPA, 2003).

Other essential costs would include installing additional monitoring wells for monitoring the SRWCGT system (which can cost up to and in excess of $5,000 per well depending on site factors), labor and analytical costs for long-term groundwater monitoring, and the labor and analytical costs for sampling/analyzing contaminant uptake by the tree tissue. The latter cost item is deemed essential, especially for situations where the practitioner desires a potential cost recovery from harvesting an SRWC. Several researchers have estimated the cost of producing an SRWC, resulting in wide disparities due to varying input and production assumptions (e.g., production locations, cost categories, etc.). Cited production costs of SRWCs range from $1,000 to $1,600/acre (English and Cody).

5.1.3 Scaled-Up Costs for a Hypothetical Site

The SRWCGT system at the CGC site is a relatively small field-scale application, consisting of two plantations, each having just seven rows of trees. To simulate a full-scale system, costs have been presented for an application at a 200,000-ft^2 (~4.6 acres) hypothetical site, consisting of 960 trees divided evenly between two 120 x 400-ft plots (Table 16). Some of the cost figures for the hypothetical site were derived from actual costs and design criteria used for the CGC system. The cost breakdown used follows guidelines recommended in the *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* (Federal Remediation Technologies Roundtable [FRTR], October 1998). In most instances, specific estimated costs values presented in this section have been taken from an economic analysis conducted by the USEPA SITE Program (USEPA, 2003).

5.1.3.1 Capital Costs

Capital costs are considered fixed costs for this cost assessment and are subdivided into six subcategories as shown in Table 16 (FRTR, 1998). Each of these cost categories is discussed in the following paragraphs.

Mobilization, Setup, and Demobilization

Technology mobilization, setup, and demobilization includes the transportation (freight on board) or delivery of equipment, facilities, and personnel to and from the site as well as the setup of temporary facilities and utilities necessary for the construction and startup of the remedial technology (FRTR, 1998). Most of the labor for an SRWCGT system could be staffed from a local or regional office, thus avoiding substantial travel and lodging costs. Setup is anticipated to be incorporated into the site work costs (discussed latter). There are no demobilization cost associated with an SRWCGT system, just restoration (also discussed later). Overall, costs associated with this category are not specific to a tree-based phytoremediation project and thus are not included.

Table 16. Cost Reporting for a Hypothetical Full-Scale SRWCGT System (USEPA, 2003).

Cost Category	Sub Category	Costs ($)
FIXED COSTS		
1. Capital costs	Mobilization, setup, and demobilization	0
	Planning/preparation	57,500
	Site work	41,700
	Equipment and appurtenances Structures Process equipment	39,733
	Start-up and testing	0
	Other capital costs Nonprocess equipment Engineering and Management Support	0
Subtotal $138,933		
Variable costs		
2. Operation and maintenance	Labor	108,000
	Materials	22,480
	Utilities and fuel	12,900
	Equipment cost (if rental or lease)	0
	Performance testing/analysis	172,855
	Other direct costs	0
Subtotal $316,235		
3. Other technology-specific costs	Long-term monitoring, regulatory/institutional oversight, compliance testing/analysis	5,000
	Soil/sludge/debris excavation, collection, and control	0
	Disposal of residuals	7,500
		Subtotal 12,500
		TOTAL COSTS (based on 2001 U.S. dollars)
		TOTAL TECHNOLOGY COSTS ~ 467,700
		Quantity treated 200,000 ft^2
		Unit cost 2.34/ft^2

Planning and Preparation

Planning and preparation includes permits and licenses (e.g., air emission and water discharge permits and license fees associated with technology use); regulatory interaction; written plans such as work, sampling and analysis, health and safety, community relations, and site management plans (FRTR, 1998). Although it is assumed that the hypothetical site has already been extensively investigated, a data review is still needed to identify potential data gaps in the design and operation of the phytoremediation system. The estimated cost for data review is $2,500, based on a project scientist billing out at $50/hr and spending approximately 50 hours researching existing literature and identifying data gaps. Also, permitting and reporting requirements have to be accounted for in the planning/preparation stage. Permit costs are estimated at $5,000 and report preparation costs are estimated at $50,000. Total cost for planning/preparation is therefore estimated at $57,500.

Site Work

Site work includes all work necessary to establish the physical infrastructure for a technology application and activities necessary to restore a site to preremediation conditions or to meet the specifications of a site restoration plan. Preparation activities, such as clearing and grubbing; earthwork; and construction of utilities, culverts, treatment pads, foundations, and spill control structures are also included (FRTR, 1998). These costs for the hypothetical SRWCGT site include well installation, pre-installation characterization, ground preparation, tree planting, installation of an irrigation system, other miscellaneous site preparation tasks, and site restoration.

Additional Monitoring Well/Piezometer Installations: An additional 5 monitoring wells and 10 piezometers are assumed for the hypothetical site to supplement an existing 15-well network to better define aquifer characteristics. The cost for drilling, installing and developing these additional monitoring wells/piezometers is estimated at $24,000. The subcontract cost per 6-inch diameter well and piezometer is estimated at $2,800 and $800 respectively. This assumes that monitoring wells require the use of a truck-mounted drill rig for drilling and installation. The less expensive GeoProbe® system could be used to install the piezometers. The total subcontract cost associated with this subtask is estimated at $22,000. Labor associated with subcontract oversight and the collection of 30 soil samples during drilling is estimated at $2,000 (based on a midlevel geologist billing out at $50/hr and working a total of 40 hours).

Pre-installation Characterization Studies: Pre-installation characterization studies address data gaps identified during the data review subtask. The acquired data helps decide tree type; planting density; total trees needed to achieve hydraulic control; the number, position and dimensions of the tree plots; specialized planting needs; irrigation requirements; and the types and amounts of fertilizer and soil conditioners. Specific studies might include:

- Aquifer testing of new and existing wells to better define aquifer hydraulic properties (i.e., hydraulic conductivity, transmissivity, and hydraulic yield).

- Groundwater and soil sampling to better define certain geochemical and physical properties, such as DO, redox potential, macro and micro nutrients, pH, conductivity, particle size distribution, soil moisture, plus evidence of intrinsic biological activity and reductive dechlorination in the rhizosphere of native trees.

- Evapotranspirational studies (Sapflow measurements and root biomass studies) conducted on several species of existing trees in the study area to evaluate current removal of water from the aquifer (saturated zone) and provide a means of estimating higher attainable levels of transpiration.

- Tissue samples (i.e., leaves, stems and roots) collected from several species of existing trees in the study area to analyze contaminant uptake in plant organ systems and metabolic transformation potential.

Pre-installation characterization study costs are estimated at $5,000, and include labor costs for purging monitoring wells; collecting water level measurements and groundwater samples from existing and new wells; collecting tree tissue samples from existing trees; and recording various field measurements needed to fill data gaps. Pre-installation characterization groundwater sampling would be limited to just the new monitoring points and 10 existing monitoring wells (i.e., 25 wells sampled). Water level measurements would be obtained from all 45 site wells. Tree tissue samples will be obtained from 12 to 13 existing trees (i.e., total tissue samples collected). The $5,000 estimate is based on two junior level scientists billing out at $50/hour working five 10-hour days.

Ground Preparation: Ploughing and discing of tree-planted areas is necessary for fertilizer infiltration, increased soil porosity and root growth, and mixing of nutrients and conditioners (i.e., organic matter, drainage-enhancing media, etc.) into the soil. The plots will also be ripped and/or trenched to plant trees and set irrigation system piping. Costs associated with this subtask consist of labor and equipment rental fees. Based on the size of each plantation and experience gained during the demonstration, ground preparation activities are estimated at 5 days, with associated labor costs estimated at $1,250 (based on using a technician billing out at $25/hour and a workday estimate of 10 hours). Discing, ploughing, ripping, and trenching will utilize equipment rented locally. Ploughing and discing equipment (tractor) will likely be needed for 5 days at a rate of $1,500 per week. A disc attachment rents for $200/day. A walk-behind trencher will probably be rented for a week for $750 (it may also be needed to install irrigation lines). Total rental costs for ground preparation activities are estimated at $2,450. Total cost for ground preparation work at the hypothetical site are estimated at $3,700 (about $804/acre).

Tree planting: Tree planting labor costs are estimated at $2,500. This assumes (1) 960 trees, divided evenly between two 120 x 400-ft plots, are needed at the hypothetical site;(2) that the trees are placed in rips or trenches created to the desired depth and backfilled with a rooting mixture of fertilizer, organic-rich soil, and other amendments; and (3) two technicians costing $25/hour work a total of five 10-hour days to complete the job.

Irrigation System Installation: Based on the layout and size of the tree plots at the hypothetical site and experience gained during the demonstration, the tasks associated with installing an

irrigation system include the following: (1) assembling components (i.e., PVC mainlines and sub-mains, drip tubing arrays, emitters, valving, backflow preventors, pressure regulators, filters, and end caps); (2) trenching; (3) staking; and (4) testing the system. Total costs for irrigation system installation is estimated at $4,250, which includes 7 days of labor costs estimated at $3,500 (based on two technicians costing $25/hour and working seven 10-hour days) and rental costs for a trencher is based upon a weekly rate of $750.

Miscellaneous Site Preparation Tasks: Include connecting to a water supply ($1,000) and installing a small lockable tool shed for storing equipment and supplies ($200). Solar panels and rechargeable batteries can power all monitoring equipment, thus eliminating an electrical power main hookup. Potential costs not included are rentals of an office trailer equipped with a phone and fax and a portable toilet. An office/supply trailer estimate was based on a $500/month rental over a 10-year remediation period. A potential significant expense is electricity, which is needed to provide lighting, air conditioning, and heat to the office/storage trailer. Generic site preparation responsibilities such as site clearing, demolition, grading, road building, surveying, utility clearance, staging area construction, site fencing, auxiliary facility construction, office trailer rental, and main utility connections are assumed responsibilities of the property owner/manager. These nontechnology-specific costs are not included.

Site Restoration: Most of the site restoration costs at a phytoremediation site consist of proper abandonment of all wells. Trees can most likely be left in place unless an arrangement has been made to harvest and sell the wood. Because well abandonment requirements vary from state to state, abandonment costs can vary as well. Use of a drill rig to abandon the 5 additional wells at the hypothetical site would cost approximately $250, and the charge for well abandonment would be approximately $8 per foot. This price includes labor, materials, insurance, and taxes. The five additional wells at the hypothetical site represent 100 linear feet that will require abandonment. The total cost for demobilization is estimated at $1,050.

Equipment and Appurtenances

This category includes structures, equipment, and appurtenances; construction and installation of remedial technology components and materials, including technology parts and supplies to make the technology operational; and upgrades, modifications, or replacements to technology components (FRTR, 1998). Structures are either permanent or semipermanent components (i.e., typically not removed from the project site for use elsewhere). For a phytoremediation technology, structures include monitoring wells, whose material costs are incorporated into installation costs. Process equipment, on the other hand, would consist of a substantial list of items that add up to a significant cost (Table 17).

Table 17. Process Equipment for a Hypothetical Site (USEPA, 2003).

Equipment Item (Number Required)	Cost ($)
Irrigation system components (PVC mainlines, submains, drip tubing arrays, emitters, valving, backflow preventors, pressure regulators, filters, caps, etc.)	2,000
Central main data logger (1 unit)	2,750
Multiplexers (3 units)	1,500
Main telemetry system (1 unit)	1,650
Pressure transducers and cabling (10 units)	18,000
Soil moisture probes (18 units)	6,000
Sapflow probes (32 units) [3]	3,593
Weather station (1 unit) including solar panel and batteries	3,000
Groundwater sampling equipment (includes pumps and water quality meters)	1,240
Total process equipment cost	39,733

<u>Start-up and Testing</u>

This cost category includes activities associated with start-up of the treatment technology, such as establishing operating conditions, shakedown, and training of operation and maintenance (O&M) personnel (FRTR, 1998). Since there are no operating conditions or system shakedown per se for a phytoremediation technology, therefore there are no associated costs.

5.1.3.2 <u>Operation and Maintenance Costs</u>

Operation and maintenance costs are considered variable cost. They include labor, materials and consumables, utilities and fuel, rented or leased equipment, performance testing and analysis, and other direct costs—each of which is discussed below.

<u>Labor</u>

Labor costs associated with the hypothetical site would be limited to general ground maintenance tasks and monitoring and sampling events. Ground maintenance tasks would consist of the periodic removal of dead branches, pruning, replanting and clearing dead trees, weeding, grass mowing, and applying fertilizers and pest and disease control substances. Labor associated with ground maintenance would likely be conducted monthly and occur primarily during the growing season (7 months out of the year). Ground maintenance tasks would likely require a landscaper working an 8-hour day each month. Assuming a landscaper labor rate of $50/hour, ground maintenance labor for the term of treatment (10 years) is estimated at $28,000. The amount of ground maintenance ultimately required can vary considerably. Sites with higher visibility require more attention then remote sites. After the canopy of the trees has closed, the undergrowth rarely needs cutting. Planting shade-tolerant ground cover that requires little or no maintenance can reduce maintenance costs.

Labor associated with monitoring and sampling is reduced somewhat by using data logging instrumentation, which enables real-time remote access and monitoring of information pertaining to tree growth, hydraulic conditions, and soil moisture. Monitoring and sampling events typically involve physical tree measurements (i.e., tree height, canopy width, and tree trunk

diameter), additional water level measurements, calibration checks on automated monitoring systems, groundwater sampling and tree sapflow measurements. Two monitoring/sampling events are assumed required annually during the growing season. Each event would require two junior-level scientists at $50/hour, working five 8-hour workdays to complete. Total labor costs associated with monitoring and sampling are estimated at $4,000 per event, or approximately $80,000 over a 10-year period, assuming biannual sampling.

Sampling events should be more common in the early years as the trees establish themselves. Once anaerobic groundwater conditions and maximum hydraulic influences are established, the remedial project manager might consider petitioning regulators for a less stringent monitoring program to reduce costs.

Materials

Materials include consumable supplies, process materials, bulk chemicals, and raw materials. This covers ongoing operations as well as preventative and corrective maintenance activities (FRTR, 1998). Consumable and supply items for this cost scenario would include fertilizer and soil conditioning materials, mulch, pest and disease control materials, the trees, ancillary supplies for monitoring equipment (tubing for peristaltic pump and tool shed), miscellaneous expendable landscaping supplies (rakes, shovels, pruners, garden sprayers, etc.) and health and safety supplies. Piping and fittings for the irrigation system are estimated to cost $2,000 (with a 20% salvage value). The SITE Program economic analysis based consumption of fertilizer, soil conditioner, and pest and disease control materials on a total tree plot area of 96,000 ft^2 and 10 years of treatment (USEPA, 2003). The estimated costs for fertilizer/soil conditioners and pest/disease control materials were $3,000 and $2,000, respectively. Since the hypothetical site is approximately twice that area, these costs are doubled to $6,000 and $4,000, respectively.

Tree cost will vary based on geography and tree species. For the 200,000 ft^2 hypothetical site an, estimated total of 960 trees are required. Assuming volume discounts will enable a purchase price of $0.50 per tree, total tree cost would total $480. The tool shed cost is estimated at $2,000. Ancillary supplies for monitoring equipment tubing, gardening supplies, and health and safety supplies are estimated at $1,000/year ($10,000 over the term of project).

Utilities and Fuel

This category includes consumable energy supplies, such as fuel, electricity, natural gas, and water. Also covered are ongoing operations, as well as preventative and corrective maintenance activities (FRTR, 1998). A major utility cost for phytoremediation projects is cellular phone service for each telemetry system operating at a site. Two telemetry systems are deemed necessary for the hypothetical site, each incurring a monthly cellular service fee of approximately $100 (approximately $12,000 over a 10-year period). A water utility service is needed for the drip irrigation system until the tree roots reach the groundwater (assumed to be about 2 years) and would be available to augment the aquifer in situations of severe drought. The water consumption for the hypothetical site is estimated at $900. No costs for electrical usage are included since solar panels and rechargeable batteries will be used to power the monitoring systems.

Rented/Leased Equipment

This category includes ownership (amortization), rental, or lease of equipment necessary for operation and maintenance of remedial technology components (FRTR, 1998). The only rented equipment required for the operation and maintenance of this technology are rental vehicles required for the periodic field work. Generators for powering groundwater sampling equipment and costs are considered are negligible.

Performance Testing and Analysis

Performance testing and analysis includes monitoring, sampling, testing, and analysis related to identifying the performance of a technology. It does not include similar activities related to the demonstrating compliance with applicable regulations and permits specific to the technology application (FRTR, 1998). Off-site analytical support is assumed needed during any sampling associated with the pre-installation characterization study and during each monitoring and sampling event conducted at the hypothetical site. As discussed previously, the purpose of samples collected during the pre-installation characterization stage is to support decisions on tree type, plot placement and dimensions, number of trees, planting density, fertilizer schedule, the types and amounts of soil conditioners needed, and irrigation system design. Pre-installation characterization analytical costs for the hypothetical site are estimated to be $38,455, based on the following analyses:

- Twenty-five groundwater samples analyzed for VOCs, inductively coupled plasma (ICP) metals, TOC, common ions, and pH

- Thirty soil samples analyzed for VOCs, ICP metals, TOC, pH, % moisture, porosity, particle size distribution, nitrate-nitrites, and phosphates

- Twenty-five tree tissue samples analyzed for VOCs.

It is estimated that 15 groundwater samples will need to be collected for off-site analyses during each monitoring and sampling event. These events would monitor changes in VOC contaminant concentrations and the spatial distribution of VOC contaminants in the groundwater. Analytical costs associated with monitoring and sampling events are estimated at $13,440 per year, assuming two sampling events per year. Analytical costs for monitoring and sampling events conducted over the 10-year treatment period are estimated at $134,400. Total analytical costs for all monitoring and sampling events are estimated at $172,855.

Other Direct Costs

Other direct costs include all O&M costs associated with a specific technology that were not previously identified. These costs generally include nonprocess equipment overhead and health and safety associated with the O&M of the technology. Nonprocess equipment overhead includes maintenance and repair of office and administrative equipment, such as database processing and computer equipment, safety equipment, and vehicles. Health and Safety costs

include those for personal protective equipment (PPE) and monitoring personnel for health and safety (FRTR, 1998).

5.1.3.3 Other Technology-Specific Costs

Other technology-specific costs are also considered variable costs. They include long-term monitoring, regulatory/institutional oversight, compliance testing and analysis, and disposal of residuals—each of which is discussed below.

Regulatory Oversight and Compliance Testing/Analysis

This category includes monitoring, sampling, testing, and analysis related to demonstrating compliance with applicable regulations and permits specific to the technology application; however, it does not include similar activities related to monitoring the performance of the technology (FRTR, 1998).

For this hypothetical cost estimate, it is assumed that the performance monitoring previously discussed will also be sufficient to demonstrate compliance with applicable regulations. This is because tree-based phytoremediation technologies are typically applied to sites having relatively low levels of groundwater contamination, for which long-term remediation goals are established.

It is assumed that repairs will be required periodically to the drip irrigation system. It may have to be drained during the winter months to prevent ice damage. Estimated repair costs for the hypothetical site's irrigation system are estimated at $1,000. It is also possible that the weather station, soil moisture probes, and data logger may get damaged over the course of treatment due to grounds keeping activities, lightning strikes, etc.; therefore, it is assumed that $4,000 would be needed for replacement parts.

Debris Excavation, Collection, and Control

Excavation, collection, and control include activities associated with excavation, collection, and control of contaminated soil, sludge, and debris prior to ex situ treatment. Staging of contaminated media such as collection of drums is also included (FRTR, 1998). Although the SRWCGT system is an in situ process, there are associated staging opportunities. The only excavation required for a SRWCGT system is that required for planting trees. These costs are incorporated into site work under the main capital cost category.

Disposal of Residues

Disposal of residues includes activities associated with both on- and off-site disposal of primary and secondary waste residues from the operation of the technology, such as treated soil disposed of off-site (FRTR, 1998). Based on the classification and disposal requirements for the types of contaminants found in the subsurface at the hypothetical site, the cost to manifest, transport, and dispose of an assumed 15 drums of residuals was estimated at $500/drum. The total cost to dispose of these drums is estimated to be $7,500. Additional drums might be generated for the disposal of contaminated PPE items. It is assumed that no more than 2 PPE drums of PPE

contaminated enough to require special waste handling and disposal would be generated over the course of treatment. Disposal of these drums would be nominal and has not been included here.

5.2 COST ANALYSIS

When implementing a tree-based phytoremediation technology, the major cost drivers are the amount of monitoring required to adequately evaluate the process over the life of the project and the labor required to prepare and maintain the tree plantations and to conduct sampling operations. This assumes that the general site conditions are conducive to the technology (e.g., a shallow water table containing relatively low levels of chlorinated contaminants). Based on the EPA SITE Program for economic analysis of the scaled-up hypothetical site, these two cost categories combined make up more than 60% of treatment costs. Analytical services were estimated to be 37.1% of costs, and labor for ground maintenance and sampling 23.2% of costs (USEPA, 2003). It should be noted that at the CGC site, the trees were planted using traditional planting techniques. If deep-rooted planting techniques are required, the labor cost would increase.

Table 18 presents a sensitivity analysis that focuses on these two cost categories (i.e., those most sensitive). Since the demonstration project at the CGC site was heavily research-oriented, there are substantial cost-saving opportunities in the area of analytical services. The pre-installation characterization analytical cost most likely should be kept the same ($38,455) due to the importance of correctly sizing and siting tree plantations. However, two significant cost subcategories associated with long-term performance monitoring are analytical services at $134,400 and labor associated with that monitoring at $80,000. If both these subcategory costs are halved by conducting the monitoring annually instead of twice per year, a significant reduction is realized—from $214,400 to $107,200 for long-term monitoring and 22.9% for the overall project costs.

Table 18. Sensitivity Analysis for TCE Remediation with a SRWCGT System.

Scenario	Description	Total Technology Cost	Original Technology Cost [1]	Difference (+/-)	% Increase (+) or Decrease (-)
1	Decrease in long-term groundwater monitoring	$361,250	$468,450	- $107,200	- 22.9 %
2	Increase in long-term groundwater monitoring	$682,850	$468,450	+ $214,400	+ 45.8 %
3	Elimination of well and piezometer installation	$444,450	$468,450	- 24,000	- 5.1 %

[1] Based on USEPA SITE Program economic analysis for a hypothetical site (USEPA, 2003).

On the other hand, if quarterly monitoring is required (as is the case for certain RCRA sites), those same long-term monitoring costs would double, as shown in Table 18, Scenario 2. In Scenario 3, the same site has been deemed adequate as to the number of monitoring wells and piezometers required for adequate site characterization. Therefore, since no additional monitoring points are needed, the $24,000 spent on installing these additional monitoring points is eliminated from the total project cost and creates a modest savings.

One other cost driver that is unique to tree-based phytoremediation systems is the tree planting technique. If shallow groundwater contaminated with low-level nitrates, phosphates, hydrocarbons, or chlorinated hydrocarbons is encountered at a site that is suitable to growing an SRWC, consideration should be given to employing the technology developed by the DOE before employing any proprietary deep planting methods (USEPA, 2003). Deep planting methods are typically used to direct roots downward to reach the water table quicker relative to normal root growth. These methods can be considerably more expensive than traditional planting techniques.

5.3 COST COMPARISON

It should be noted up-front that use of a tree-based phytoremediation technology should first and foremost be considered after comparing its effectiveness and cost to natural attenuation. If site-specific natural attenuation processes are at work and capable of reducing mass, toxicity, mobility or volume of halogenated hydrocarbons in the soil and groundwater, the site in question *may not* be considered a candidate for a phytoremediation intervention. Natural attenuation remedies would incur similar analytical and monitoring costs (including predictive modeling) but would not incur the capital costs.

Aside from natural attenuation, the SRWCGT system employed at CGC can be compared to conventional technologies that either degrade contaminants or control the migration of contaminants. Such treatment technologies include ex situ pump-and-treat systems, and in situ bioremediation systems (including in situ barriers).

Estimated costs for such technologies are documented in ESTCP and SITE reports, and several present cost estimates for application at sites having characteristics similar to those at the CGC site. Although direct comparisons among different sites is not prudent, general comparisons can be made, especially among the unit costs (i.e., costs presented on an area or volume basis). Table 19 presents such costs for the CGC SRWCGT system as compared to other technologies costed at sites having contamination of relatively shallow groundwater.

Table 19. Cost Comparison of the SRWCGT System to Other Conventional/Innovative In Situ Technologies.

Technology and Site Characteristics							
	SITE INFORMATION					Cost Estimates [1]	
Technology/ Source	Site Name	Target Compound	Depth to Aquifer/ Aquifer Thickness	Area/Vol. Treated [2]	Treat. Time	Total Real-World Cost	Unit Cost
SRWCGT (USEPA, 2003)	Carswell NAS-JRB	TCE	2.5–4m (8.2-13.1′)/ 0.5–1.5m (1.6-4.9′)	200,000 ft^2 74,000 yd^3	10 yr.	$468,000	$2.3 ft^2 $6.3 yd^3
Air Sparging (ESTCP, 2000)	Port Hueneme	MTBE	5 ft/10 ft	60′ x 75′ 4,500 ft^2	6 mo.	$268,000	$60 ft^2
Propane Biosparging Biobarrier (ESTCP, 2003)	Port Hueneme	BTEX, MTBE	10 ft/10 ft	3,600 ft^2 ~1,300 yd^3	2 yr.	$172,000	$48 ft^2 $130 yd^3
PHOSter™ In Situ Bioremdiation (Gallardo et al, 2002)	ITT Night Vision	1,1-DCA, *c*DCE, VC	5–15 ft/40–45 ft	23,000 ft^2 900,000 ft^3 33,000 yd^3	2 yr.	$370,000	$16 ft^2 $11 yd^3
[1] Total cost rounded to three significant digits							

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

The design, installation, monitoring, and maintenance requirements for a tree-based phytoremediation system is highly site-specific. As a result, a number of factors could affect overall cost, including, but not limited to:

- Total treatment area
- Distribution and magnitude of contamination
- Climate
- Hydraulic framework of the site
- Physical and chemical properties of the soil
- Treatment goals.

Treatment area would logically factor into the number of trees needed, the amount of time required to install the system (ground preparation activities, installing an irrigation system, planting the trees, installing system monitoring stations), the amount of nutrients, soil conditioners, mulch, pest and disease control substances, the volume of water consumed for irrigation purposes, as well as the man-hours needed to perform periodic maintenance tasks.

Contamination distribution and magnitude affects the placement, alignment, and dimensions of tree plantations. If the objectives of the project focus on hydraulic control (i.e., reducing the mass flux of groundwater contamination transported across the planted areas) then it would be necessary only to place plantations in a position enabling them to intercept contaminants released from the most downgradient source. The contaminant type and magnitude of contamination (assuming it is a halogenated species, as was the case at the CGC) would factor into the tree species chosen and the overall time needed to remediate the site. Availability of trees species known to be more tolerant to higher concentrations or to specific chemicals may factor into cost.

Climatic factors such as the start and length of the growing season, annual precipitation, and the amount of solar radiation control the amount of time during the year that the trees exert a hydraulic control on the aquifer, biologically enhance subsurface conditions, and remove contaminants via evapotranspiration. Climatic factors also determine the need for an irrigation system during drought conditions (i.e., to augment the aquifer and prevent the trees from dying). Shorter growing seasons could lengthen the time needed to reach remediation goals.

The hydraulic framework of the site (i.e., aquifer size and yield, groundwater velocity and flow direction, depth-to-groundwater, aquifer thickness, and the homogeneity and grain size of aquifer materials) should be used as a guide when deciding on tree density, plot size, and the number of plots needed. Hydraulic conditions at the site would also control the time needed for the trees to reach full hydraulic and transpirational potential, either shortening or lengthening the time the system starts to have a significant hydraulic impact on the site. Although research has shown that hydraulic control is the principle mechanism responsible for reductions in the mass flux of contamination transported across the planted area during the early stages of tree-based treatment, other mechanisms, especially microbially mediated reductive dechlorination may become just as

prominent after the third or fourth season. In fact, reductive dechlorination might be the most important mechanism operating during the dormant season.

The physical and chemical properties of the soil would include soil moisture retention, soil moisture profiles, drainage, and infiltration rates, which would determine the need and design of an irrigation system to help jump-start the trees. These soil properties will also determine the need for providing a type of groundcover that would force the trees to seek out the aquifer as a source of water rather than becoming dependent on rainwater infiltrate. Other soil properties that have the potential for impacting cost would be nutrient availability and the organic content of the soil. This would determine the amounts of fertilizer and soil conditioners needed over the course of the project and also affect the maintenance schedule, possibly increasing the man-hours needed.

Treatment goals would be site-specific. Certain goals may be based on specific soil and/or groundwater cleanup criteria or based on a site-specific receptor risk. Remedial goals at a site may fall into two categories—source removal or source control. Whatever the remedial goals may be, certain design features and the time needed to effect the necessary changes would ultimately affect total cost.

There are several different approaches to planting trees currently available. These range from deep auguring individual poles to the capillary fringe employing proprietary planting techniques to employing SRWC techniques. These planting approaches have their indications, contradictions, and their various champions within the phytoremediation arena. Depending on soil conditions, tree plot areas may require plowing, tilling, and discing to facilitate fertilizer infiltration, increase soil porosity, ease planting, and foster vigorous root growth.

6.2 PERFORMANCE OBSERVATIONS

When designing for hydraulic control at an SRWCGT system, it is important to keep the remediation goals in mind. In other words, it may not be desirable to achieve full hydraulic control at a site if full control would adversely affect the groundwater/surface water system downgradient of the site. To use the demonstration site in Texas as an example, the receptor at that site is Farmers Branch Creek. This creek has very low flow (less than 1 ft^3/sec) during the summer months (peak transpiration). The optimal performance at such a site may be to keep the plume from discharging into the creek without drying up the creek, particularly since hydraulic control is only one mechanism that contributes to the cleanup of a groundwater plume by an SRWCGT system. A groundwater flow model of a potential site is ideal for addressing such design concerns.

In general, the amount of hydraulic control that can be achieved by an SRWCGT system is a function of site-specific aquifer conditions. A planted system can be expected to have a greater hydrologic effect on an aquifer at a site that has an initially low volumetric flux of groundwater as opposed to a site where the flux of contaminated groundwater is significantly greater. The parameters of hydraulic conductivity, hydraulic gradient, saturated thickness, and aquifer width in the treatment zone all contribute to the volumetric flux of groundwater through a site. The horizontal hydraulic conductivity at the demonstration site in Fort Worth, Texas, is approximately 6 m/day. The natural hydraulic gradient is close to 2% and the saturated thickness

of the aquifer is between 0.5 and 1.5 m. Volume of water in storage in an aquifer will also affect system performance. Although the current study did not investigate the effect of aquifer depth, it is possible that a greater percentage of total evapotranspiration could be derived from an aquifer with a shallower water table.

6.3 SCALE-UP

The planting approach employed in the Carswell demonstration has been used by the pulp and paper industries worldwide at much larger scales relative to the demonstration site. There is information in the public domain developed by DOE's Oak Ridge National Laboratory Biomass/Biofuel Group with regard to the selection, planting, care, and harvesting of various trees and grasses amendable to short rotation energy and fiber crops (USEPA, 2003).

6.4 OTHER SIGNIFICANT OBSERVATIONS

Regarding economics, the two major factors are size of tree plantations and the amount of monitoring needed. These two factors will directly affect labor and analytical costs. Trees are not a major cost consideration, especially if saplings and/or whips are used.

6.5 LESSONS LEARNED

The demonstration data indicated discernable advantage in planting caliper trees over the less expensive whips. Generally, the closer trees are planted, the sooner a plantation may achieve closed canopy, although closely spaced trees increase the chance for disease. There is a body of literature on short rotation wood culture as guidance with regard to tree spacing in an SRWCGT system (USEPA, 2003).

Monitoring groundwater at the Carswell site also produced several insights itself. The first is that traditional groundwater level measuring devices will likely cease to operate properly or give erroneous readings due to roots from the planted cuttings hanging them up. The iron in the steel float can interact with the groundwater to produce greatly elevated hydrogen levels. This is an artifact and does not reflect the influence of the plantation subsurface biomass on the geochemistry of the groundwater. The problems with traditional floats were resolved at the Carswell site by employing Design Analysis WATERLOG H310 pressure transducers. These cost approximately $1,000 each and work by detecting changes in pressure, which relates to changing water levels. It is important that this pressure sensor be clamped or tied down to a fixed location. If the pressure is subject to open flow, it is likely that the readings will be inconsistent. This no-flow condition is achieved by suspending the sensor from a stainless steel drop cable and using a weighted ballast or sinker (USEPA, 2003).

Based on modeling, the technology was supposed to achieve full canopy closure in 12 years and beyond, which would result in maximum transpiration (resulting in a predicted drawdown of 12-25 cm at center of drawdown cone). However, Braun et al (2004) have graphically shown that, as of January 2003, mortality rates in both plantations have been significant—189 (43%) of trees in the whip plantation had died, and 111 (26%) of the trees in the caliper trees have either died, been stunted by beaver activity, or altered by human activity.

Thus, a lesson learned may be the connection between tree growth/tree mortality and the lack of water. Per Braun et al (2004), cottonwood tree mortality rates approached 90% where groundwater levels were between 12 and 13 ft bls and a relatively constant 25% where groundwater levels were less than 10 ft bls. This may have been caused by overplanting. Poplars need to be present in sufficient numbers to effectively draw down the water table through transpiration, but not so dense that they remove all the available water and then die (Jacobs Engineering Group, 1996).

6.6 END-USER ISSUES

Phytoremediation is currently being practiced by some professionals with backgrounds in agronomy, biochemistry, hydrology, chemical engineering, sedimentology and industrial hygiene to clean up shallow groundwater and soil contaminated with various metals and organics. Because phytoremediation is in its commercial infancy, the people who employ phytoremediation have often designed projects with methodologies developed from personal experience. This knowledge is considered to be proprietary and zealously guarded even though much of this information is already in the public domain. An extensive body of public domain information on the physiology and development of SRWC has been developed by DOE. This information provides detailed guidance on how to select and prepare potential sites.

Phytoremediation may be most appropriate for treating chlorinated solvent plumes that exhibit Type 3 behavior (i.e., plumes occurring in areas that are lacking an adequate amount of native and or anthropogenic carbon and have concentrations of DO > 1.0 mg/L). Reductive dechlorination does not occur under Type 3 conditions. Type 3 conditions commonly prevail at DoD sites (e.g., the TCE plume at the CGC), resulting in very large unattenuated plumes.

Before initiating a phytoremediation corrective action for shallow groundwater, it is imperative to determine if natural attenuation processes (i.e., biodegradation, dispersion, sorption, or volatilzation) are able to achieve site-specific remedial objectives within a comparatively reasonable time frame. If site-specific natural attenuation processes are at work and capable of reducing mass, toxicity, mobility, or volume of halogenated hydrocarbons in the soil and groundwater, the site in question may not be considered a candidate for a phytoremediation intervention (USEPA, 2003). Because there is normally an adequate supply of electron acceptors in most hydrologic settings, fuel plumes naturally attenuate and degrade faster than they move. Plumes of chlorinated solvents can also naturally attenuate, but almost 80% of the time they do not due to the lack of electron donors (Chapelle, 2000).

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Despite the fact that most of what is known about this technology is derived from laboratory and small-scale field studies, phytoremediation approaches have received higher public acceptance than most conventional remedial options. Since these systems can be used either along with or sometimes in place of intrusive mechanical cleanup methods, obtaining regulatory compliance and acceptance may be easier than for conventional counterparts.

Plant 4 (the suspected source of TCE contamination) is on the National Priorities List (NPL). Therefore, the TCE contamination is being remediated in accordance with the Comprehensive

Environmental Response, Compensation, and Liability Act (CERCLA) as amended by the Superfund Amendments and Reauthorization Act (SARA). The SRWCGT system at the CGC site meets most of the SARA criteria since it is an in situ treatment technology (i.e., treatment occurring in place), in which removal of the contamination is expected to be permanent and protective to human health and the environment; the volume and mobility of halogenated organics in the soil and groundwater is reduced to help prevent the migration of contamination off-site or to uncontaminated water supplies; the toxicity of the waste media (soil or groundwater) is reduced; and the treatment is cost effective.

Other major regulatory requirements that may apply to the CGC site may include the Clean Air Act (CAA), which limits the emission of 189 listed hazardous pollutants; the Clean Water Act (CWA), which establishes federal, state, and local discharge standards; and the Resource Conservation and Recovery Act (RCRA), which defines hazardous wastes and regulates their transport, treatment, storage, and disposal. Examples of how each of these regulations could affect a tree-based phytoremediation system include:

- RCRA—Applicable to tree-based phytoremediation systems if RCRA-defined hazardous wastes are present. For example, if contaminated drill cutting waste from installing trees, monitoring wells, or for collecting soil samples is considered a RCRA waste, a permit issued by the state may be required to operate the system as a treatment, storage, and disposal (TSD) facility.

- CAA—Fugitive emissions from the tree-based phytoremediation system may come from soil conditioning and borehole drilling activities and from periodic sampling activities. Soil moisture should be managed during system installation to prevent or minimize the impact from fugitive emissions. No air permits are required for the tree-based phytoremediation system operated at the CGC.

- CWA—Other than the tree's capacity to pump groundwater, phytoremediation technologies generally do not involve the mechanical pumping, treatment, and discharge of surface water and groundwater. In a few rare cases where contaminated groundwater occurs at depth, mechanical pumping may be used to bring the water to the surface where it would then be applied to the plants via drip irrigation. Since this water technically would not be discharged to a navigable waterway, it is unlikely that a National Pollutant discharge Elimination System (NPDES) permit will apply.

- Safe Drinking Water Act (SDWA)—Under CERCLA (Section 121 (d) (2) (A) (ii)), remedial actions are required to meet the standards of the maximum contaminant level goals (MCLG) when relevant. Since a tree-based phytoremediation system is considered a groundwater remediation system, it is likely that these standards would be applicable. Also, Parts 144 and 145 discuss requirements associated with the underground injection of contaminated water. Therefore, if processing pumped contaminated groundwater through the plantation's drip irrigation system is an option, approval from EPA for constructing and operating this phytoremediation system in this mode will be required.

- Federal Aviation Administration (FAA) restrictions may limit tree height near airports or flight lines. Small cuttings placed in the ground can eventually become 100-foot safety impediments to aircraft operation.

- Herbicide use for weed control within plantations may be regulated by federal, state, and local regulatory agencies with respect to their purchase, labeling, storage, and application.

- Local and state regulations for codified construction requirements for backflow preventers for the irrigation system need to be checked (USEPA, 2003). The type of backflow preventer required is based on the risks posed by the substance which may flow into the potable water supply system.

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APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone/Fax/E-mail	Role in Project
Mr. Gregory Harvey	ASC/ENVR Building 8, Suite 2 1801 10th Street, Area B Wright Patterson AFB, OH 45433	(937) 255-3276 (937) 255-4155 Gregory.Harvey@wpafb.af.mil	Project Leader
Dr. Jeff Marqusee	ESTCP Program Office 901 North Stuart Street Suite 303 Arlington, VA 22203	(703) 696-2117 (703) 696-2114 jeffrey.marqusee@osd.mil	ESTCP Director
Ms. Sandra M. Eberts	USGS 6480 Doubletree Avenue Columbus, OH 43229	(614) 430-7740 (614) 430-7777 smeberts@usgs.gov	USGS Project Hydrogeologist
Mr. Steven Rock	USEPA NRMRL 26 West Martin Luther King Drive Cincinnati, OH 45268	(513) 569-7149 (513) 569-7879 rock.steven@epamail.epa.gov	USEPA SITE Program Project Leader

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

e-mail: estcp@estcp.org
www.estcp.org